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EFFECTIVENESS OF VARIOUS AGENTS FOR SUPPRESSING IGNITION OF RP-1 AND HYDROGEN UNDER FLOW CONDITIONS

by J. B. Gayle and H. E. Tubbs

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TABLE OF CONTENTS

	Page
SUMMARY	1
INTRODUCTION	1
EXPERIMENTAL	3
RESULTS	4
DISCUSSION	5
CONCLUSIONS	6
REFERENCES	37

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	Photograph of Experimental Apparatus	10
2	Schematic Drawing of Experimental Apparatus	11
3	Effects of Nitrogen on Fuel Injection Temperatures Required for Ignition of 3/0.5 Oxygen/RP-1 Mixtures	12
4	Effects of Nitrogen on Fuel Injection Temperatures Required for Ignition of 3/1 Oxygen/RP-1 Mixtures	13
5	Effects of Nitrogen on Fuel Injection Temperatures Required for Ignition of 3/2 Oxygen/RP-1 Mixtures	14
6	Effects of Nitrogen on Fuel Injection Temperatures Required for Ignition of 3/3 Oxygen/RP-1 Mixtures	15
7	Effects of Nitrogen on Fuel Injection Temperatures Required for Ignition of 6/1 Oxygen/RP-1 Mixtures	16
8	Effects of Nitrogen on Fuel Injection Temperatures Required for Ignition of 6/4 Oxygen/RP-1 Mixtures	17
9	Effects of Helium on Fuel Injection Temperatures Required for Ignition of 3/0.5 Oxygen/RP-1 Mixtures	18
10	Effects of Helium on Fuel Injection Temperatures Required for Ignition of 3/1 Oxygen/RP-1 Mixtures	19
11	Effects of Helium on Fuel Injection Temperatures Required for Ignition of 3/2 Oxygen/RP-1 Mixtures	20

LIST OF ILLUSTRATIONS (Cont'd)

Figure	Title	Page
12	Effects of Helium on Fuel Injection Temperatures Required for Ignition of 6/1 Oxygen/RP-1 Mixtures	21
13	Effects of Helium on Fuel Injection Temperatures Required for Ignition of 6/4 Oxygen/RP-1 Mixtures	22
14	Effects of Carbon Dioxide on Fuel Injection Temperatures Required for Ignition of 3/2 Oxygen/RP-1 Mixtures	23
15	Effects of Carbon Dioxide on Fuel Injection Temperatures Required for Ignition of 6/1 Oxygen/RP-1 Mixtures	24
16	Effects of Carbon Dioxide on Fuel Injection Temperatures Required for Ignition of 6/4 Oxygen/RP-1 Mixtures	25
17	Effects of Trifluorobromomethane on Fuel Injection Temperatures Required for Ignition of 3/2 Oxygen/RP-1 Mixtures	26
18	Effects of Nitrogen on Fuel Injection Temperatures Required for Ignition of 3/1 Oxygen/Ethyl Alcohol Mixtures	27
19	Effects of Nitrogen on Fuel Injection Temperatures Required for Ignition of 3/2 Oxygen/Ethyl Alcohol Mixtures	28
20	Effects of Nitrogen on Minimum Quantities of Hydrogen Required for Ignition of Mixtures Containing 3 Pounds of Oxygen	29
21	Effects of Nitrogen on Minimum Quantities of Hydrogen Required for Ignition of Mixtures Containing 6 Pounds of Oxygen	30

LIST OF ILLUSTRATIONS (Concluded)

Figure	Title	Page
22	Effects of Helium on Minimum Quantities of Hydrogen Required for Ignition of Mixtures Containing 3 Pounds of Oxygen	31
23	Effects of Helium on Minimum Quantities of Hydrogen Required for Ignition of Mixtures Containing 6 Pounds of Oxygen	32
24	Reproducibility of Fuel Injection Temperatures for the System, RP-1 + O_2 + He	33
25	Reproducibility of Fuel Injection Temperature for the System, RP-1 + O_2 + N_2	34
26	Effect of Flow Rates on Flammability Data for the System H_2 + O_2 + N_2	35
27	Effect of Flow Rates on Flammability Data for the System H_2 + O_2 + N_2 + He	36

LIST OF TABLES

Table	Title	Page
1	Summary of Results for Different Fuel/ Oxidizer/Agent Combinations	9

EFFECTIVENESS OF VARIOUS AGENTS FOR SUPPRESSING IGNITION OF RP-1 AND HYDROGEN UNDER FLOW CONDITIONS

SUMMARY

Abst

Experimental studies were carried out to determine the quantities of helium, nitrogen, carbon dioxide, and/or trifluorobromomethane needed for suppressing ignition of mixtures of oxygen with RP-1 and hydrogen under conditions of turbulent flow in a 6-inch diameter tube. The results indicated that on a weight basis the order of effectiveness of the various agents was He $\gg$ N_2 > CF_3Br > CO_2 for RP-1. For hydrogen, the order for the only two agents tested was HE $\gg$ N_2. The quantities of agents required were large enough to preclude widespread in-flight applications. The principal utility of inerting processes is probably in connection with fire prevention during static firing and prelaunch operations.

Author

INTRODUCTION

The large quantities and highly flammable nature of rocket fuels and the necessity for maintaining them in close proximity to large quantities of highly reactive oxidizing agents create major fire hazards in the event of leakages. Traditionally, fire hazards have been combatted by providing automatic fire extinguishing systems. The effectiveness of most extinguishing processes depends in part on their ability to blanket an area and to exclude oxygen from the fuel. For launch vehicle applications, the possibility of simultaneous leakages of fuel and oxidizer, coupled with the resulting flow conditions, make processes dependent on oxygen exclusion highly unattractive. Moreover, any extinguishing process, whatever the mechanism, is unlikely to be effective at a sufficient rate to preclude major damage before extinguishment.

As an alternate approach to the problem, the possibility of suppressing ignition by use of inert gases, halogenated hydrocarbons, or other agents appeared attractive provided the weight requirements were not excessive.

Coward and Jones (Ref. 1) made an extensive survey of the literature relating to the limits of flammability of mixed gases and vapors. Although some discrepancies were noted in the effectiveness of different agents, they concluded that the addition of increasing amounts of a chemically inert substance causes the flammability limits of a gas to approach each other and ultimately meet.

For methane tested in tubes of 5 cm diameter, the relative effectiveness of the more extensively studied agents decreased in the order

$CCl_4 > CO_2 > N_2 > He$ (Volume basis)

In tubes of 2.2 cm diameter, the order of effectiveness of the last three agents for several combustibles was

$CO_2 > He > N_2$ (Volume basis)

In still narrower tubes, 1.6 to 1.7 cm diameter, the order was

$He > CO_2 > N_2$ (Volume basis)

It will be seen that on the volume basis reported the order $CO_2 > N_2$ was the same in all experiments but that helium tended to rise in effectiveness as the diameter of the tube decreased.

All of the above tests were carried out under static testing conditions. Coward and Jones stated that few observations have been made on the effects of turbulence on the limits of flammability. However, for tests in which no agent was added, the lower limits of methane and ethane in air have been reported to be reduced somewhat by a "suitable amount of turbulence" produced by either a fan or by stream movement of the mixture. Similarly, the range of flammability of ether-air mixtures has been reported to be somewhat widened by stream movements. Apparently, no work has been reported on the effects of turbulence on the flammability limits of mixtures containing ignition suppressing agents.

Because of the lack of data determined for flow conditions and the uncertainty attending any attempt to apply conclusions based on small scale static tests to conditions under which leakages of rocket fuels and oxidizers are likely to occur, an experimental program was initiated to provide quantitative information regarding the relative effectiveness of selected agents for suppressing ignition under flow conditions.

EXPERIMENTAL

The experimental apparatus is shown in Figures 1 and 2. The ignition assembly consisted of a 6-inch diameter pipe nipple connected to a standard 6-inch cross by flanges. The axis of the assembly was inclined upward approximately 15 degrees to facilitate removal of liquid accumulations from the mixing chamber through a 1/8-inch drainage hole. A steel plate with a 2-inch diameter orifice was inserted between the flanges to improve mixing of the gases. The ignition source consisted of a standard airplane spark plug with a 0.025-inch gap firing at the rate of 7,200 times per minute under a potential of 10,000 volts.

The fuel preheater consisted of a coil of stainless steel tubing heated by a propane burner. In operation, a fixed flow of air was admitted to the burner, and the flow of propane was varied to obtain the desired heat output.

Liquid flow rates were measured with cavitating Venturi meters and Potter meters; gas flow rates were measured with sonic nozzles and Potter meters. Temperatures were measured with fast response thermocouples. All measurements were recorded on strip charts moving at a rate of 0.1 inch per second.

Because of the possibility that instruments in some compartments may be more susceptible to damage by pressure than by temperature, an attempt was made to determine the sound intensity (overpressure) resulting from ignition by means of a fast response pressure pickup located 4.5 feet to one side of a point 3 feet directly in front of the ignition assembly. This device was calibrated using a static pressure of 2.4 inches of alcohol to represent a sound intensity of 147 decibels; this established the upper range of the oscillograph. Because of the high chart speed (10 inches per second), initial tests on any given fuel/oxidizer/agent combination were monitored visually to determine the approximate fuel injection temperature or hydrogen flow rate at which ignition occurred. In succeeding tests, the oscillograph was turned on just before ignition was expected to occur.

For tests on RP-1, the flow rates for the ignition-suppressing agent, fuel, and oxidizer were established, and the spark plug was activated. The injection temperature of the fuel then was increased gradually until ignition occurred or the capacity of the heater was reached. The temperatures of these gases were not controlled but approximated ambient temperature except for the temperature changes caused by expansion through the flow regulator.

Tests also were made on ethyl alcohol, denatured with 5 per cent methyl alcohol. The procedure was identical to that used for RP-1.

For testing hydrogen, the procedure was varied to reflect the gaseous nature and high degree of flammability of the fuel. The fuel preheater was not used for these tests. Instead, the flow rates for the ignition-suppressing agent and oxidizer were established, and the spark plug was activated. The flow of hydrogen then was started and increased gradually until ignition occurred.

RESULTS

The results are summarized graphically in Figures 3 through 23. Because payload considerations may be the principal determining factors that govern launch vehicle applications, the results are presented on a weight basis rather than on the mole or volume basis preferred by most previous investigators. For convenience in representation and also to indicate the mass flow rates as well as the relative proportions of the various components, all mixture ratios and compositions given in this report refer to pounds per minute of each component. Thus, 3/2 and 6/4 oxygen/RP-1 mixtures have the same relative composition, but the mass flow rates for the second mixture are twice those for the first.

In general, these data show that the fuel injection temperatures required for ignition of RP-1 and ethyl alcohol were substantially independent of the inert flow rates up to some critical value beyond which slight increases in inert flow rates resulted in marked increases in fuel injection temperatures at ignition. Further increases in inert flow rates resulted in failure to achieve ignition within the range of fuel injection temperatures possible under the conditions of the test (800 to 1,000^{O}F, depending on the fuel flow rate). Similar trends were noted for tests using nitrogen, carbon dioxide, helium, and trifluorobromomethane as ignition-suppressing agents.

One series of tests was made by using a finely divided spray of water as the ignition-suppressing agent and RP-1/oxygen flow rates of 0.5/3 pounds per minute. Because much of the water separated from the gas stream and accumulated on the downstream side of the mixing orifice and in the mixing chamber, the effective water flow rates could not be determined; therefore, the data have not been included. However, it should be noted that ignition was obtained throughout the range of apparent flow rates tested, up to approximately 18 pounds of water per minute.

For tests using hydrogen, the minimum quantity of hydrogen necessary for ignition was plotted as the ordinate rather than the fuel injection temperature at ignition which was plotted for RP-1 and ethyl alcohol; however, the shape and practical significance of the curves were substantially unchanged. Specifically, the quantity of hydrogen necessary for ignition increased only slightly for increasing inert flow rates up to some critical value beyond which slight increases in inert flow rates resulted in marked increases in the minimum hydrogen flow rates necessary for ignition. Further increases in inert flow rates resulted in failure to achieve ignition for hydrogen flow rates up to five times the stoichiometric value. Similar trends were noted for tests using nitrogen and helium as ignition-suppressing agents.

For several of the sets of data, the scatter of the results appeared to be related to the inert flow rates. Standard deviation of the fuel injection temperatures for replicate tests are plotted in Figures 24 and 25 for RP-1/O_2 tests with helium and nitrogen, respectively. It should be noted that in drawing the curves for these data it was assumed that the overall behavior pattern should be relatively constant. Inspection of these curves indicates that for zero inert flow rates the standard deviations were relatively high and tended to decrease to minimum values for intermediate inert flow rates. For higher flow rates, the standard deviations increased with maximum values being determined for inert flow rates only slightly smaller than those required for complete suppression of ignition. Insufficient data were available to permit similar analysis for other inerting agents or for hydrogen/oxygen mixtures.

Sound intensity data were obtained for about 60 per cent of the runs. The results scattered widely and, therefore, are not included. However, inspection of the data for RP-1/LOX tests with different inerting agents indicated that the overpressures were highest for zero inert flow rates and decreased rapidly to minimum values for intermediate inert flow rates. Further increases in inert flow rates resulted in slightly higher overpressures.

DISCUSSION

The results summarized in Table 1 give interpolated inert flow rates corresponding to ignition of RP-1 and ethyl alcohol at a fuel injection temperature of 600°F. At this temperature, both RP-1 and ethyl alcohol are completely vaporized. Also included are interpolated inert flow rates for which the minimum quantity of hydrogen required for ignition corresponded to a stoichiometric fuel to oxidizer ratio.

Inspection of the figures given in the preceding section shows that fuel injection temperatures of 600°F and hydrogen flow rates for stoichiometric mixtures fall consistently on the steeply ascending portions of the curves. Therefore, the agent flow rates corresponding to these values may be taken as approximately equal to those required for complete suppression of ignition for purposes of discussion.

Inspection of results given in Table 1 shows that for the combinations tested the weight ratios of agent to fuel ranged from 1 for the 2/3 RP-1/oxygen mixture with helium to 83 for the 0.38/3 hydrogen/oxygen mixture with nitrogen.

The agent/fuel ratio (by wt) for trifluorobromomethane, which is widely used as a fire extinguishing agent, was 6.9 for the only combination tested; this value is approximately equal to that determined for nitrogen for the same fuel/oxidizer combination. In the use of this particular agent, it should be noted that once ignition of the mixture occurs the agent itself will support combustion even after the fuel has been shut off. It should also be noted that combustion of any mixture containing this agent would be expected to yield toxic products.

To permit comparison with results of previous investigation, the results for individual tests with H_2/O_2 using helium and nitrogen as inerting agents were converted to mole percentages and plotted on triangular coordinates as shown in Figures 26 and 27. Also included were results reported by previous investigators (Ref. 2) for tests conducted under static conditions. The previous results shown in Figure 26 were for the system H_2/Air/He. To permit direct comparison with the results of the current study, the nitrogen equivalent of the air concentration was added to the helium concentration on a mole basis to establish the total inert concentration. Inspection of the figures indicates that the scatter of the data about the visually fitted curves is surprisingly small in view of the fact that results of single determination were used. Comparison of the curves for the static tests and for the two mass flow rates studied in the current investigation suggests that departure from static conditions causes shifting of the curves toward higher oxygen concentrations and lower inert concentrations, as would be expected.

Because of the complexity of the RP-1/O_2 system, the results are not amenable to direct comparison with literature values for static systems.

The mechanism whereby the several agents tested were effective in suppressing ignition has not been definitely established. At least three mechanisms may be cited for which some supporting evidence is available. These suggest that the observed phenomena are dependent on the molar concentration, linear velocity, and/or chemical reactivity of the agent. Other mechanisms also are possible.

CONCLUSIONS

On a weight basis, the order of effectiveness of the different agents used for suppressing ignition of 3/2 oxygen/RP-1 mixtures under flow conditions was

$$He \gg N_2 > CF_3Br > CO_2 \qquad \text{(Weight basis)}$$

For the only two agents tested with oxygen/hydrogen mixtures, the order of effectiveness was

$$He \gg N_2 \qquad \text{(Weight basis)}$$

The widely accepted extinguishing agent, trifluorobromomethane, was only moderately effective for suppressing ignition of oxygen/RP-1 mixtures. Moreover, combustion of mixtures containing this agent would be expected to yield toxic products.

The quantities of helium and nitrogen needed for suppressing ignition of oxygen/hydrogen mixtures were roughly three times the corresponding values for oxygen/RP-1 mixtures. However, this comparison must be applied with caution because of the differences in test procedures used for the two fuels.

For all of the agents tested, the quantities needed for suppressing ignition were large enough to prohibit widespread in-flight applications. Therefore, the principal utility of inerting systems probably is in connection with fire prevention during static testing and prelaunch operations.

Table 1
Summary of Results
for Different Fuel/Oxidizer/Agent Combinations

	Flow Rates, Pounds Per Minute					
RP-1	1/2	1	2	3	1	4
Oxygen	3	3	3	3	6	6
Agent*						
Nitrogen	10.2	11.5	12.8	12.5	13.0	14.5
Helium	1.5	1.8	2.0		2.0	3.3
Carbon Dioxide			16.0		20.8	24.0
Trifluorobromomethane			13.8			
Ethyl Alcohol		1	2			
Oxygen		3	3			
Agent*						
Nitrogen		13.0	15.0			
Hydrogen			.38			.75
Oxygen			3			6
Agent**						
Nitrogen			31.5			37.8
Helium			3.8			7.0

* - Agent flow rates corresponding to fuel injection temperatures at ignition of 600°F.

** - Agent flow rates for which the minimum quantity of hydrogen required for ignition corresponded to a stoichiometric fuel to oxidizer ratio.

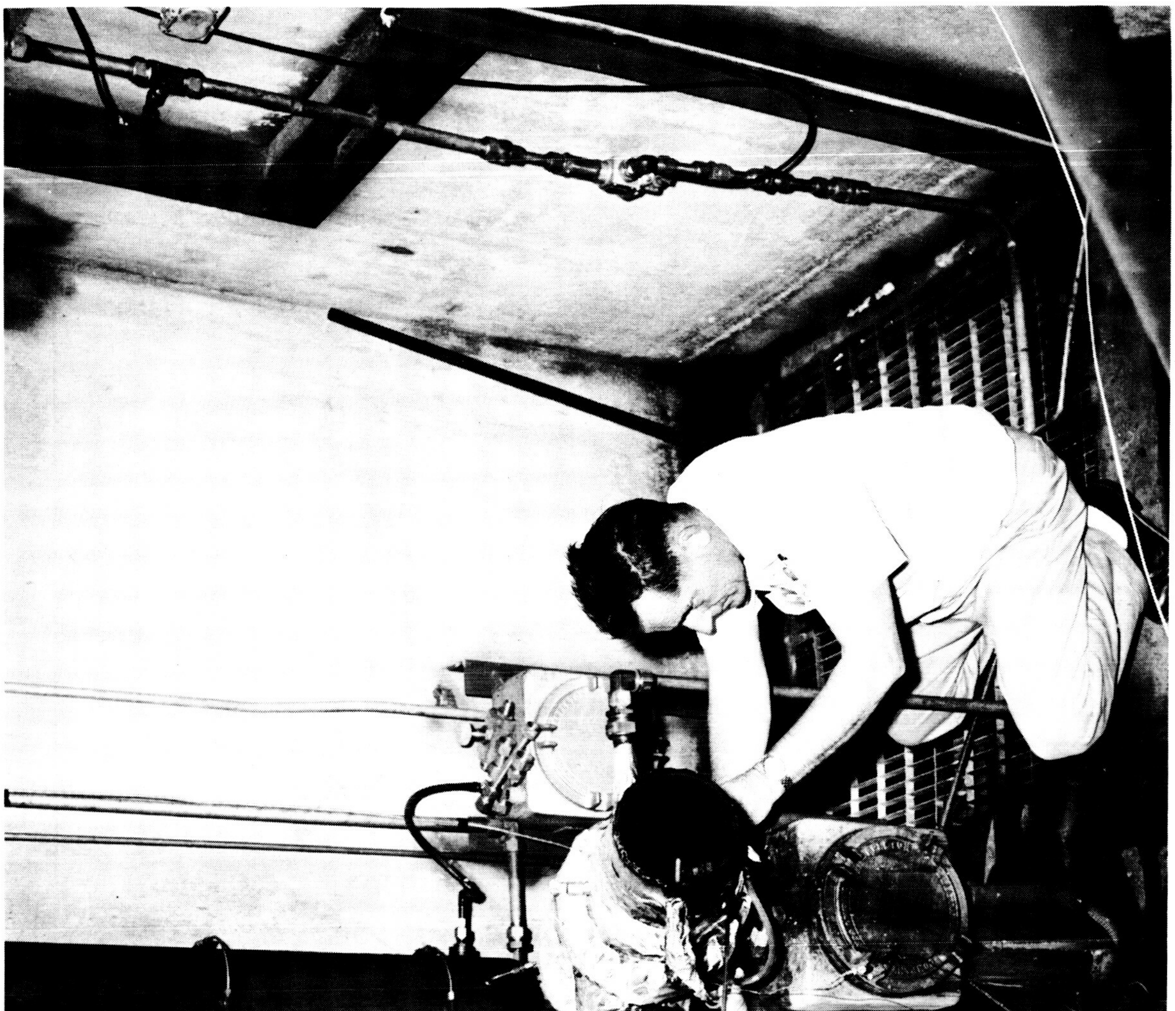

FIGURE 1. PHOTOGRAPH OF EXPERIMENTAL APPARATUS

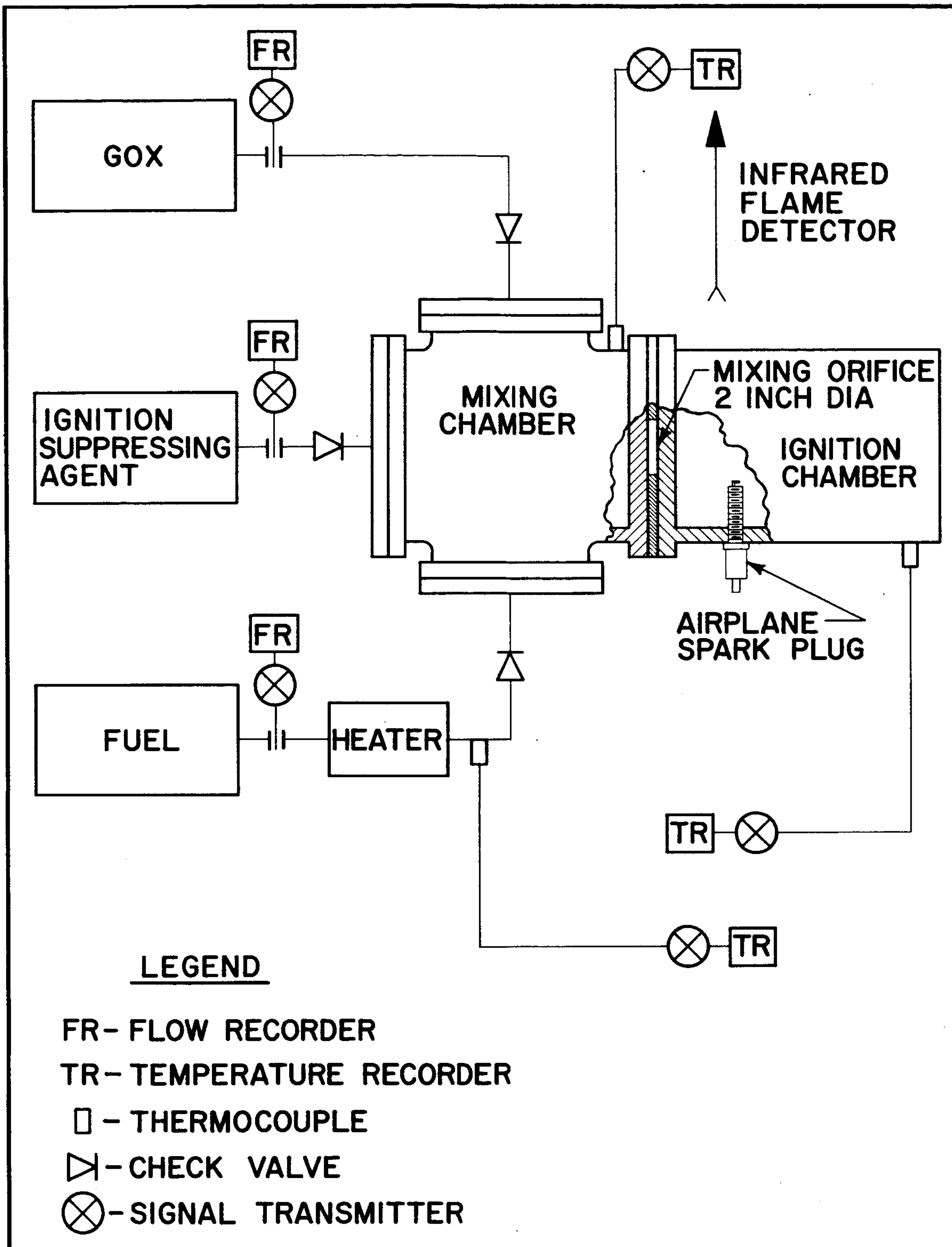

FIGURE 2. SCHEMATIC DRAWING OF EXPERIMENTAL APPARATUS

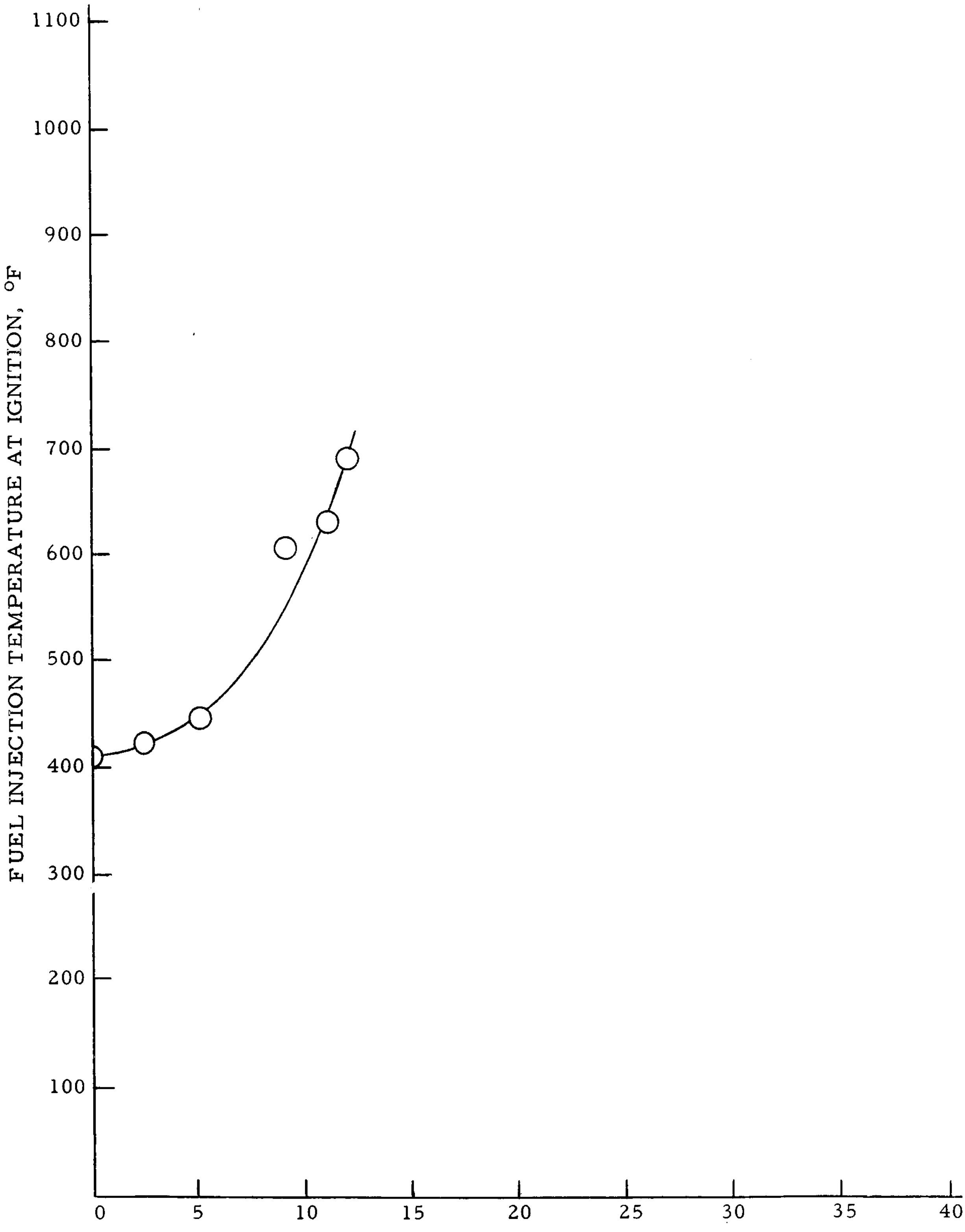

FIGURE 3. EFFECTS OF NITROGEN ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 3/0.5 OXYGEN/RP-1 MIXTURES

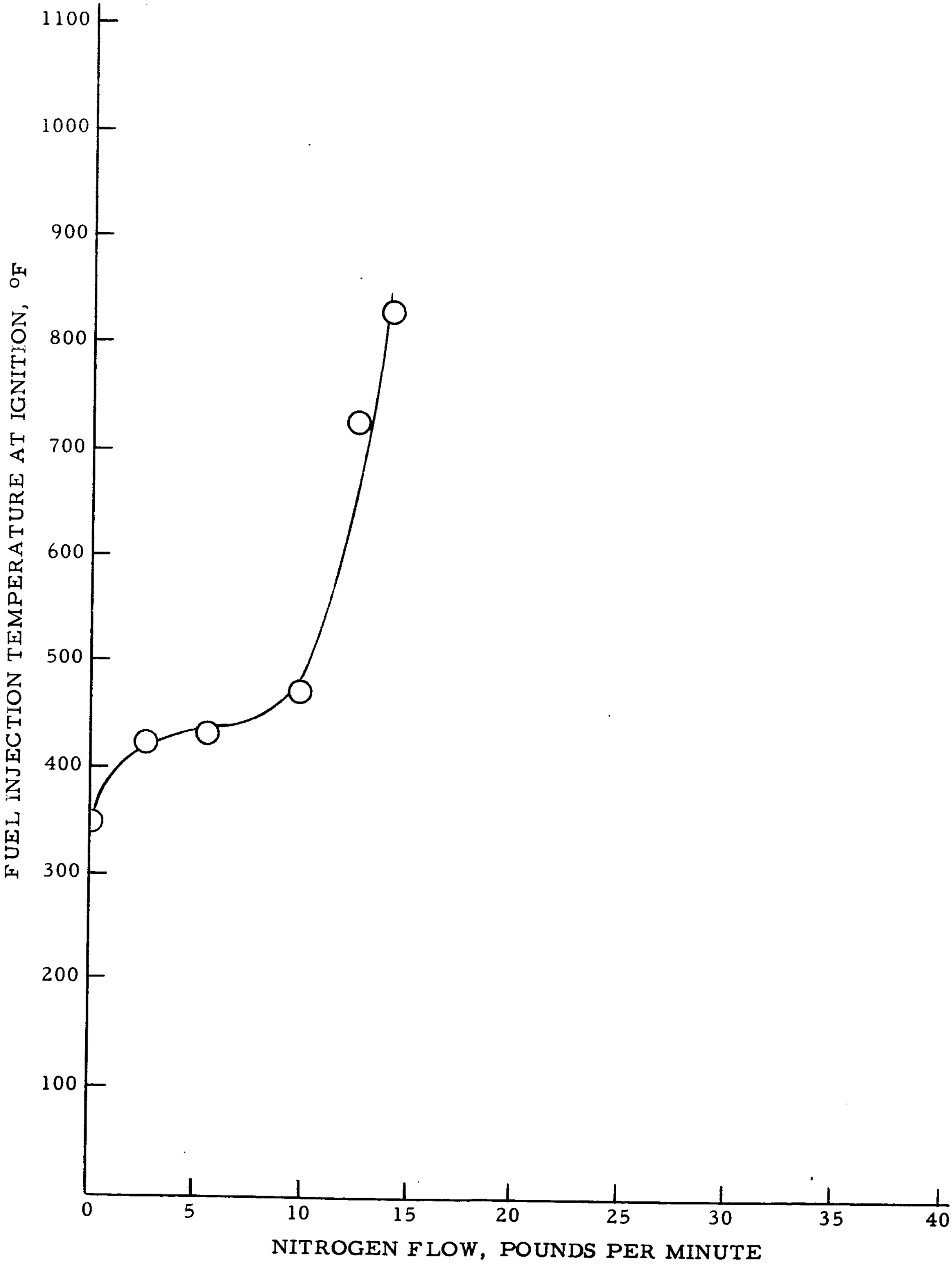

FIGURE 4. EFFECTS OF NITROGEN ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 3/1 OXYGEN/RP-1 MIXTURES

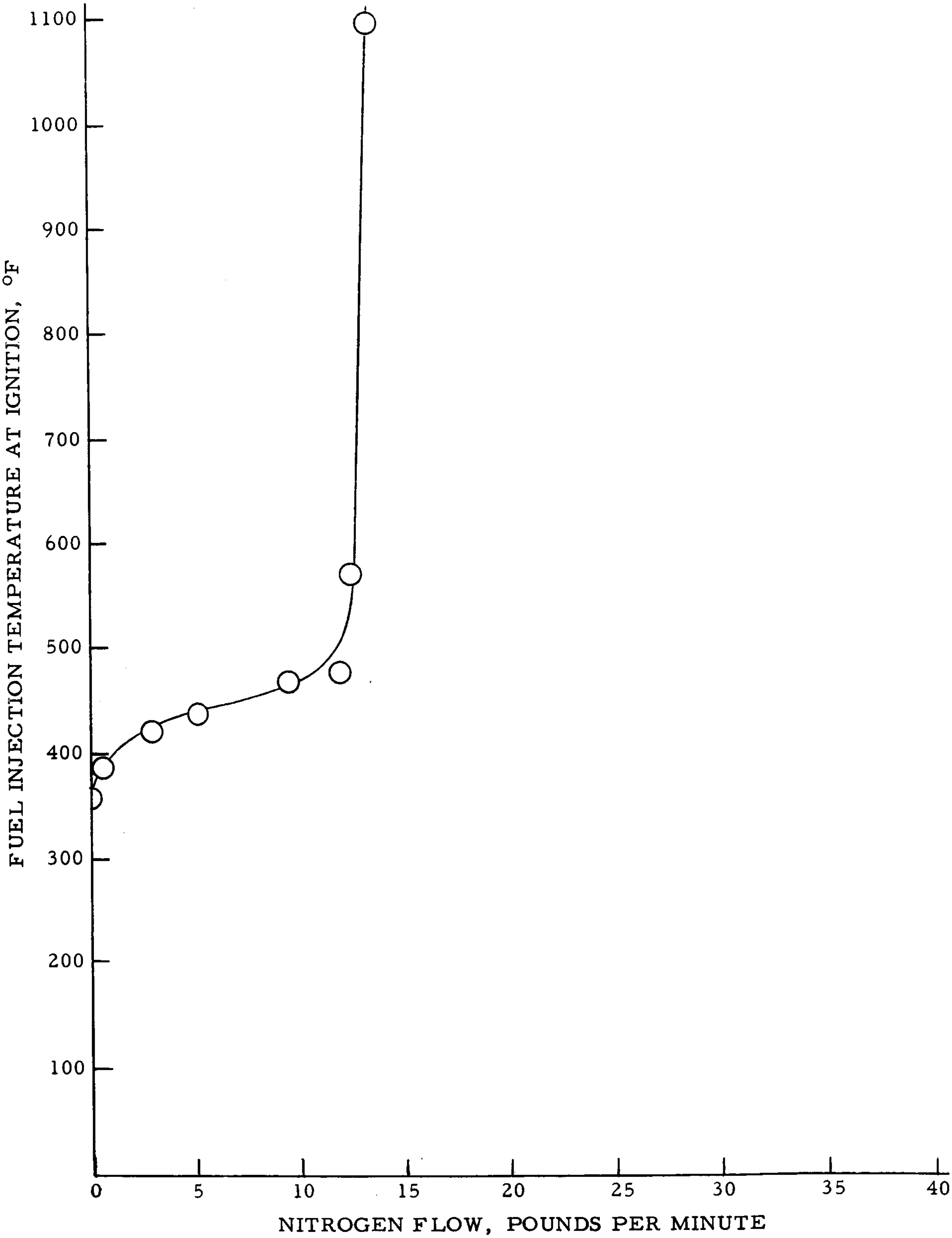

FIGURE 5. EFFECTS OF NITROGEN ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 3/2 OXYGEN/RP-1 MIXTURES

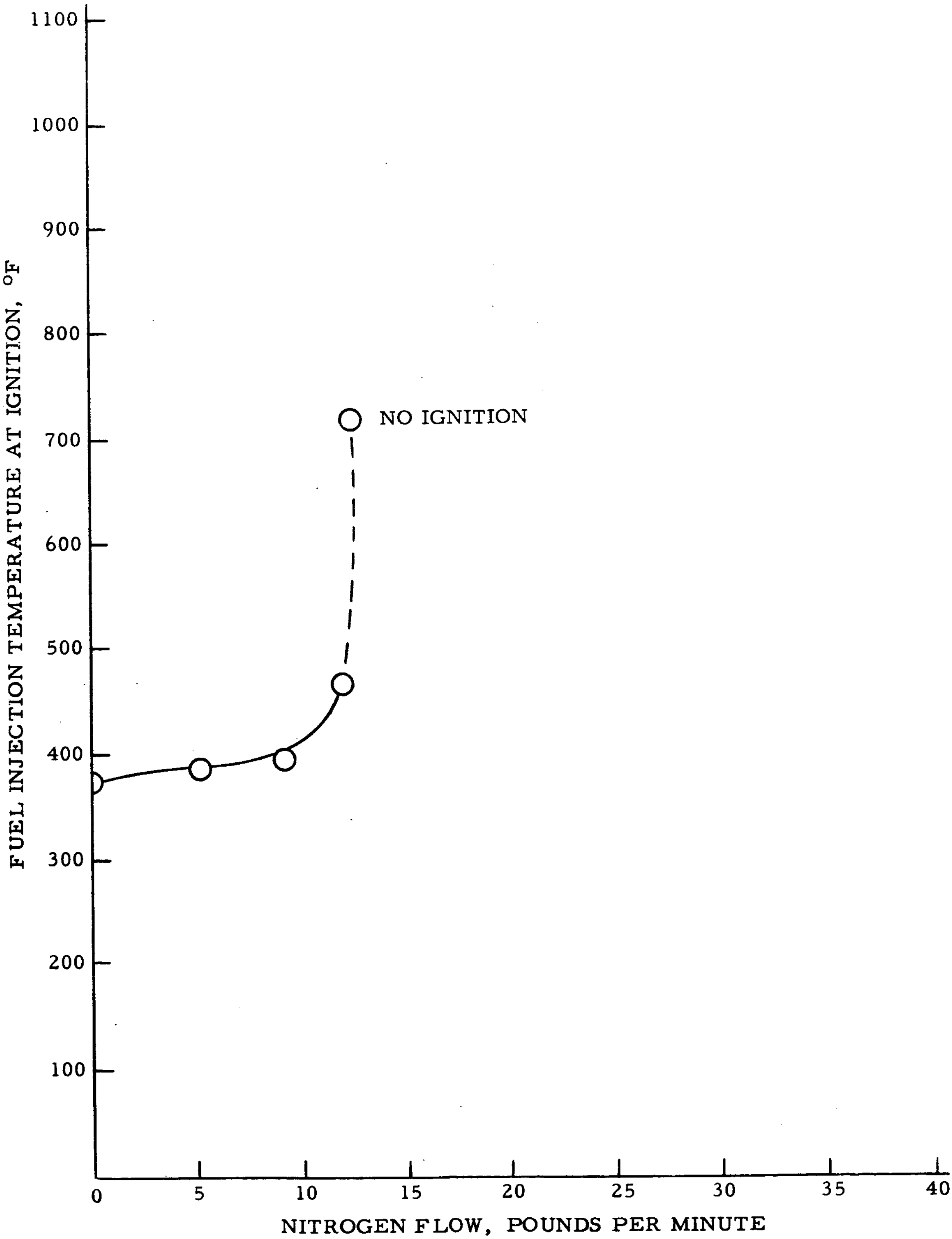

FIGURE 6. EFFECTS OF NITROGEN ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 3/3 OXYGEN/RP-1 MIXTURES

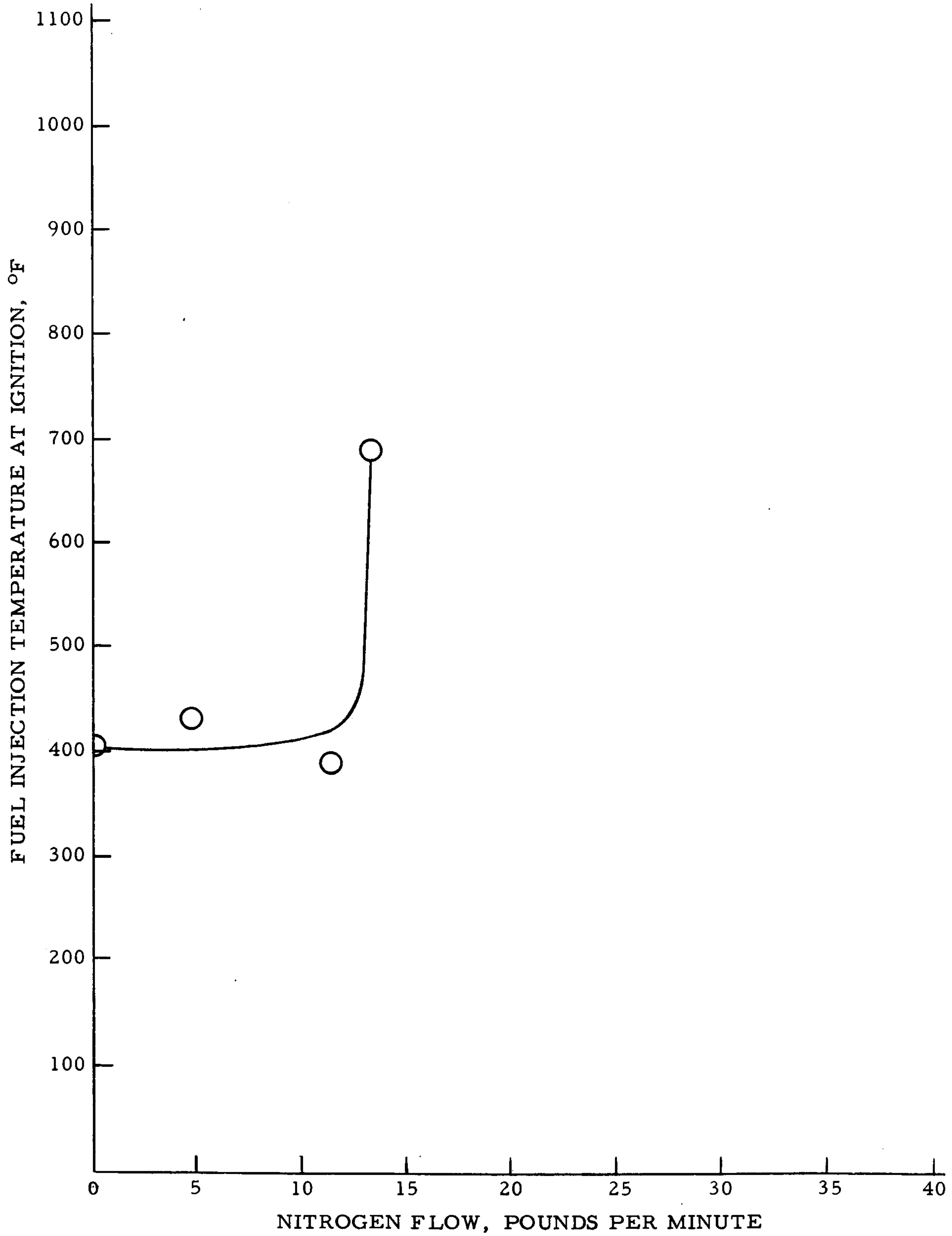

FIGURE 7. EFFECTS OF NITROGEN ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 6/1 OXYGEN/RP-1 MIXTURES

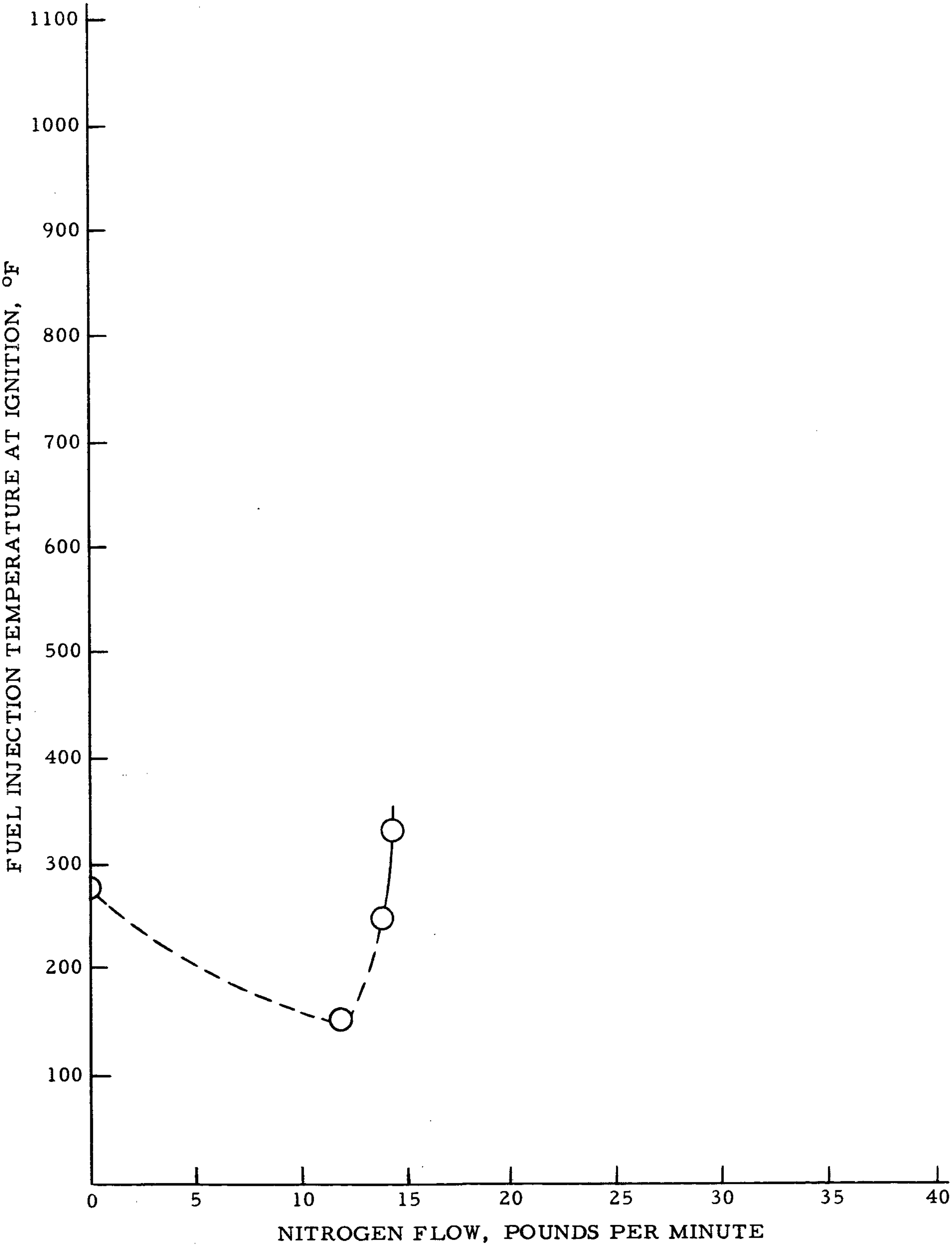

FIGURE 8. EFFECTS OF NITROGEN ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 6/4 OXYGEN/RP-1 MIXTURES

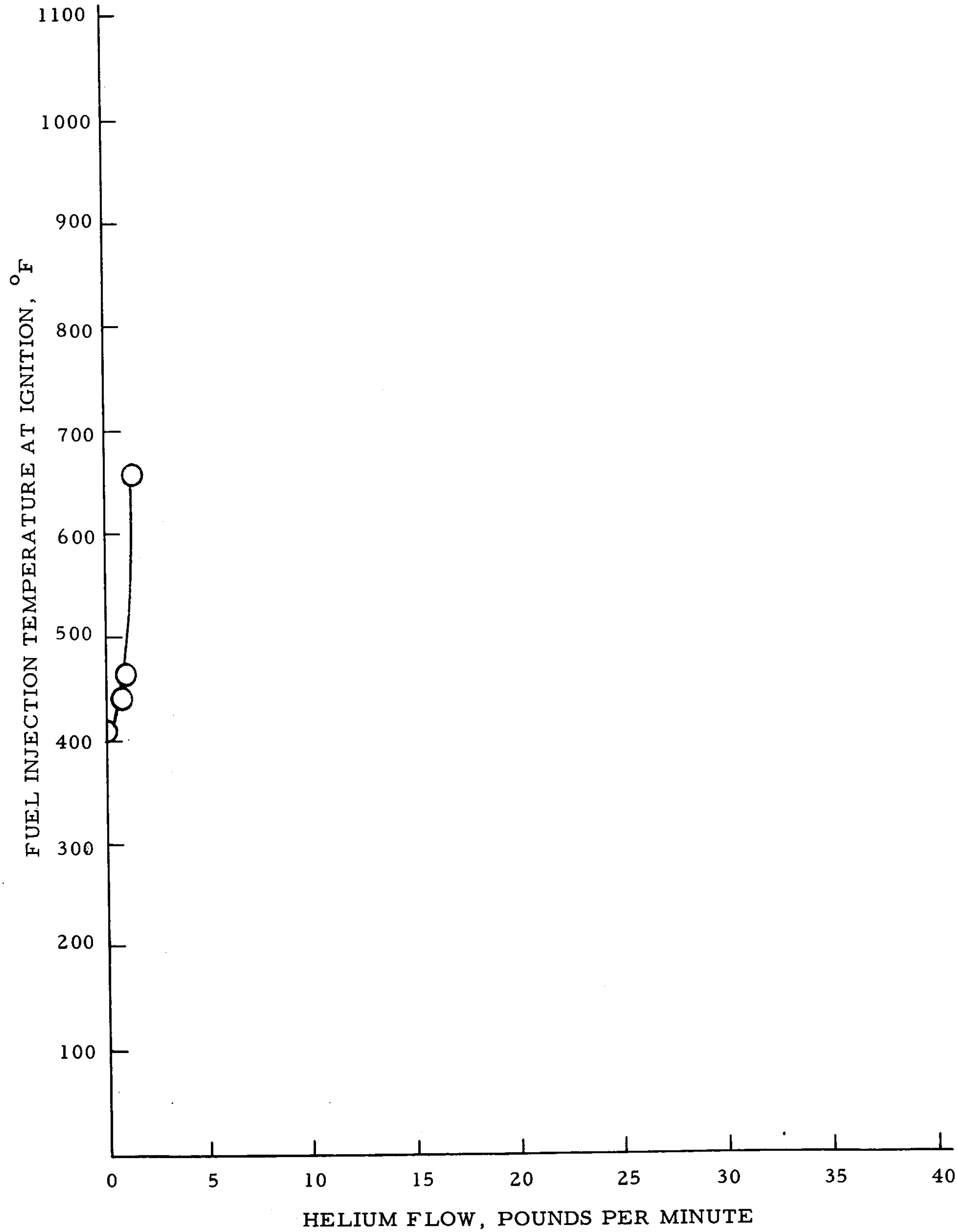

FIGURE 9. EFFECTS OF HELIUM ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 3/0.5 OXYGEN/RP-1 MIXTURES

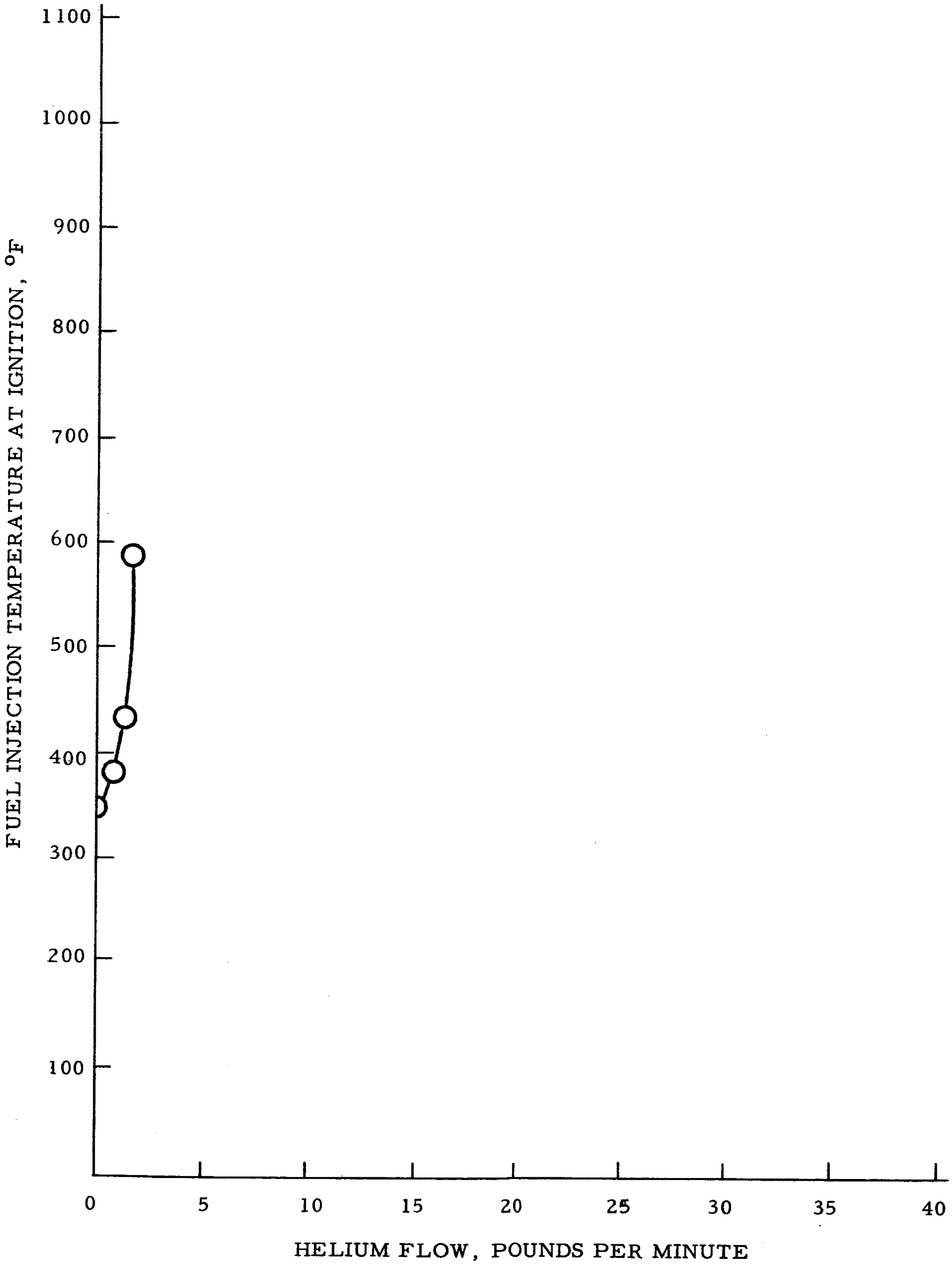

FIGURE 10. EFFECTS OF HELIUM ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 3/1 OXYGEN/RP-1 MIXTURES

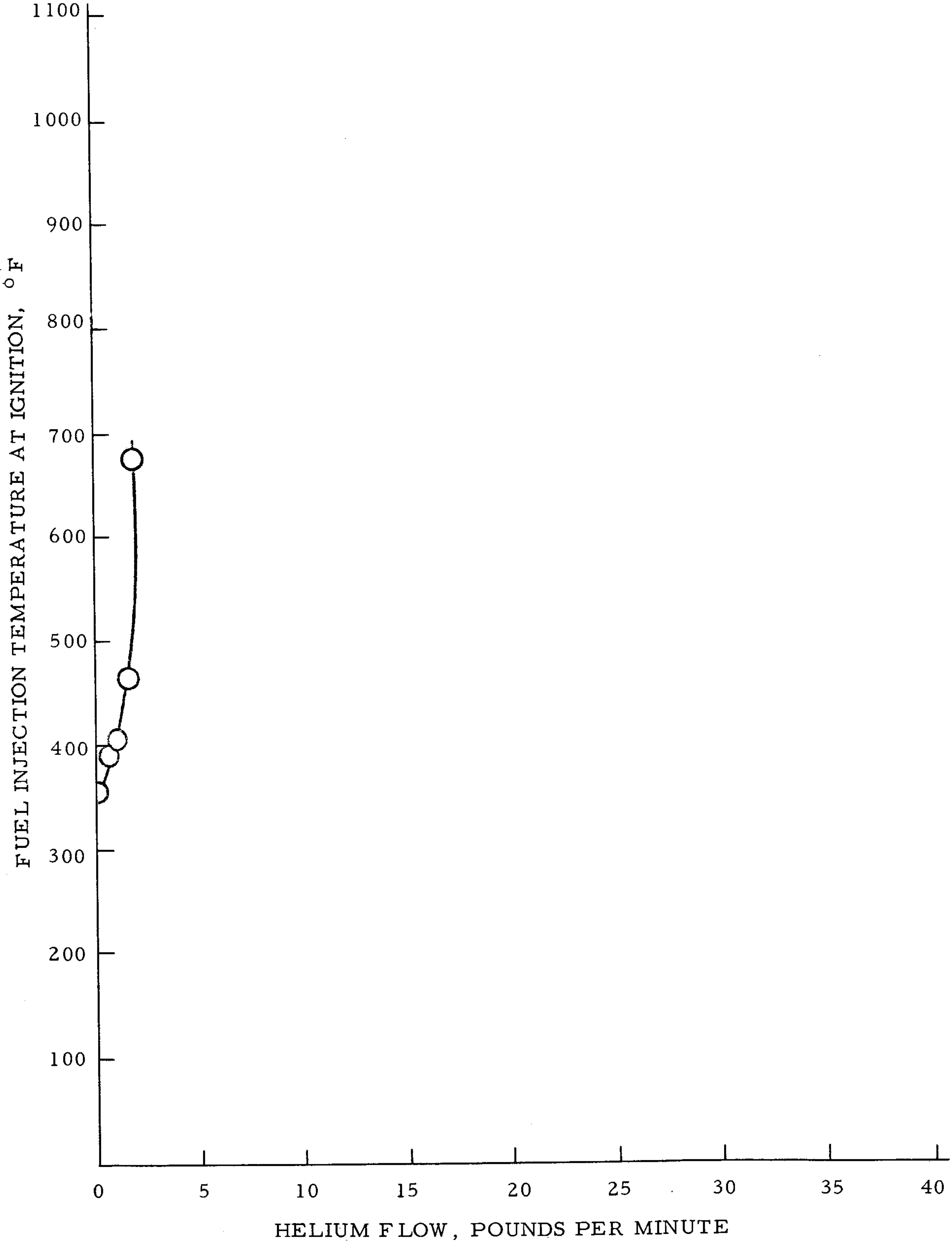

FIGURE 11. EFFECTS OF HELIUM ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 3/2 OXYGEN/RP-1 MIXTURES

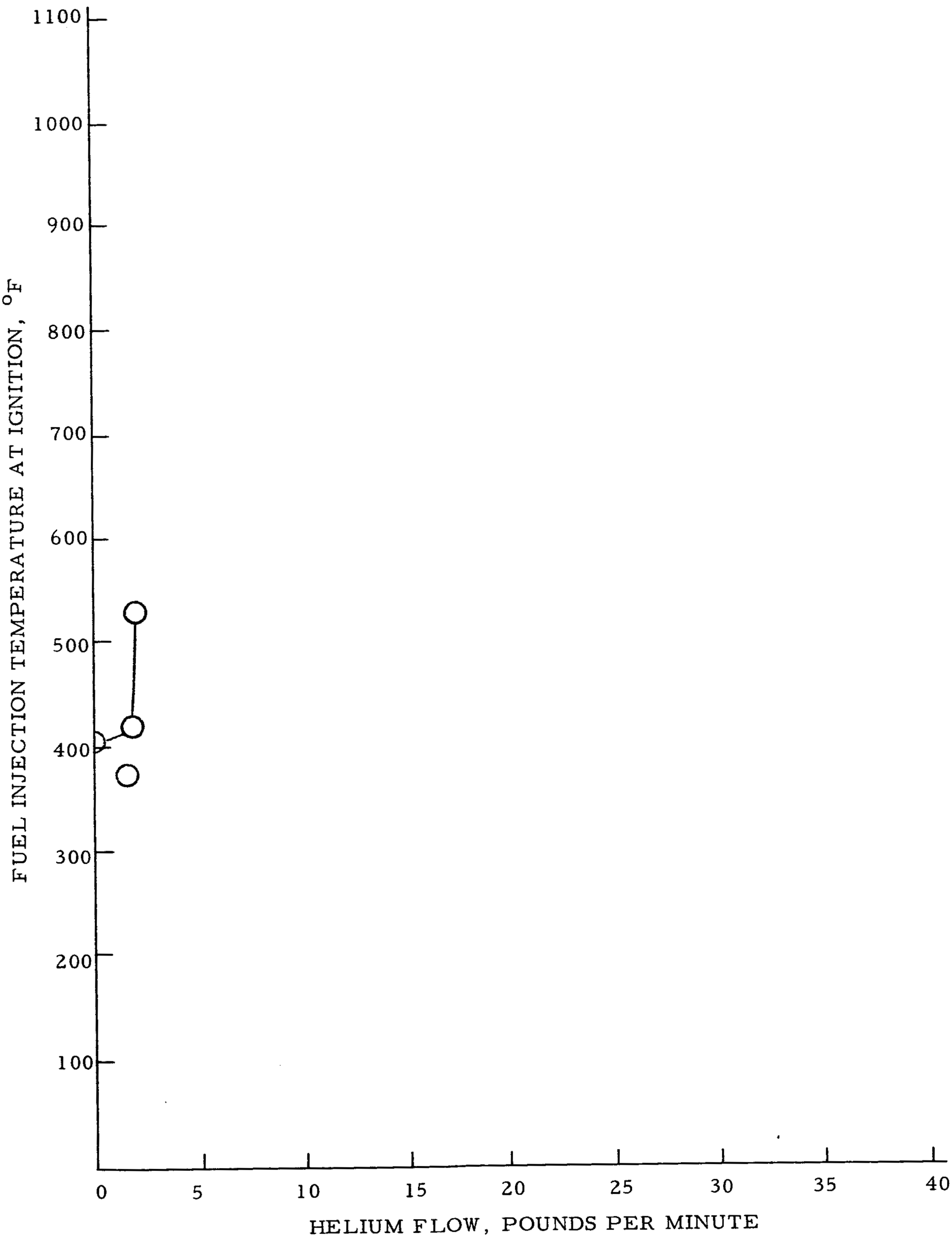

FIGURE 12. EFFECTS OF HELIUM ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 6/1 OXYGEN/RP-1 MIXTURES

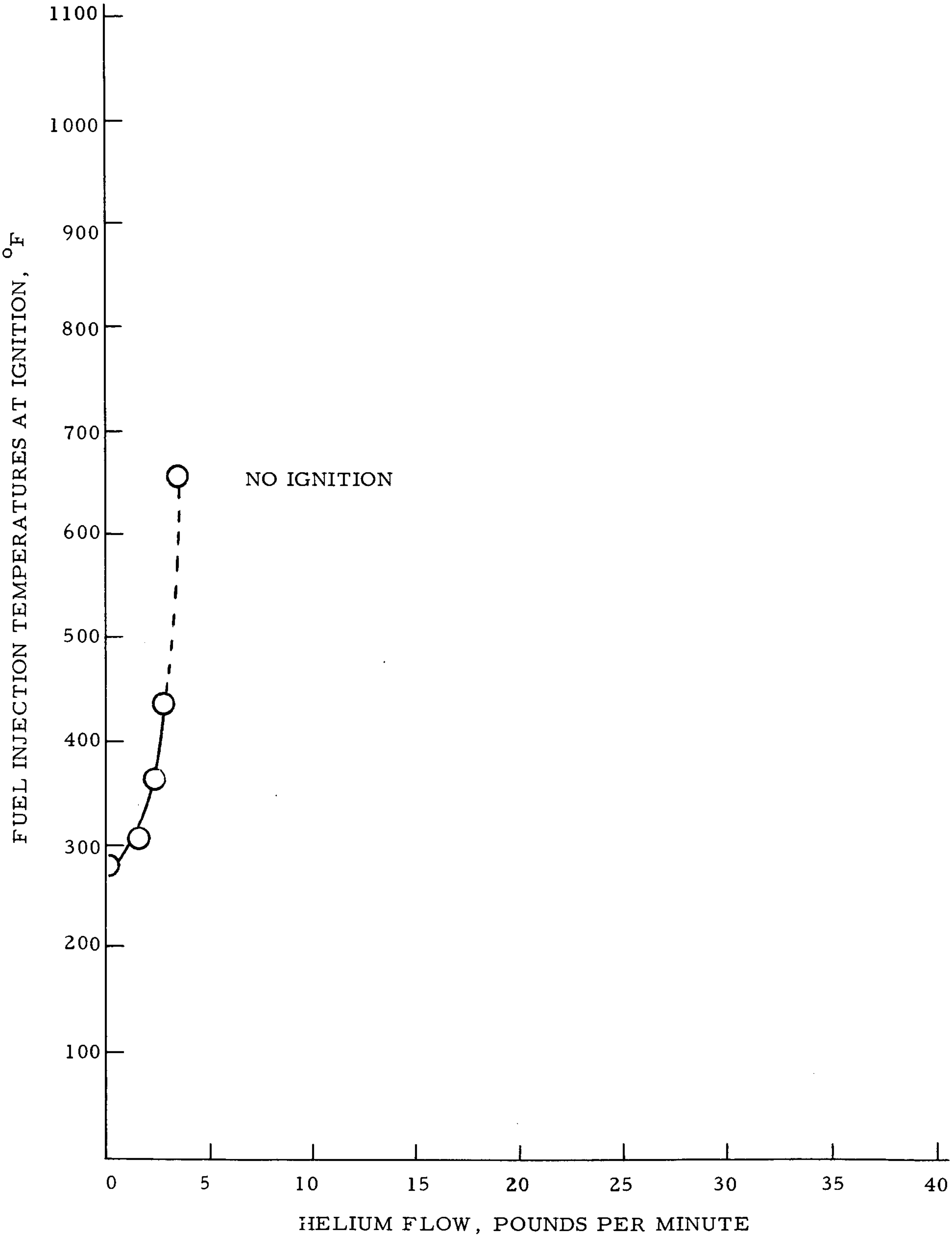

FIGURE 13. EFFECTS OF HELIUM ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 6/4 OXYGEN/RP-1 MIXTURES

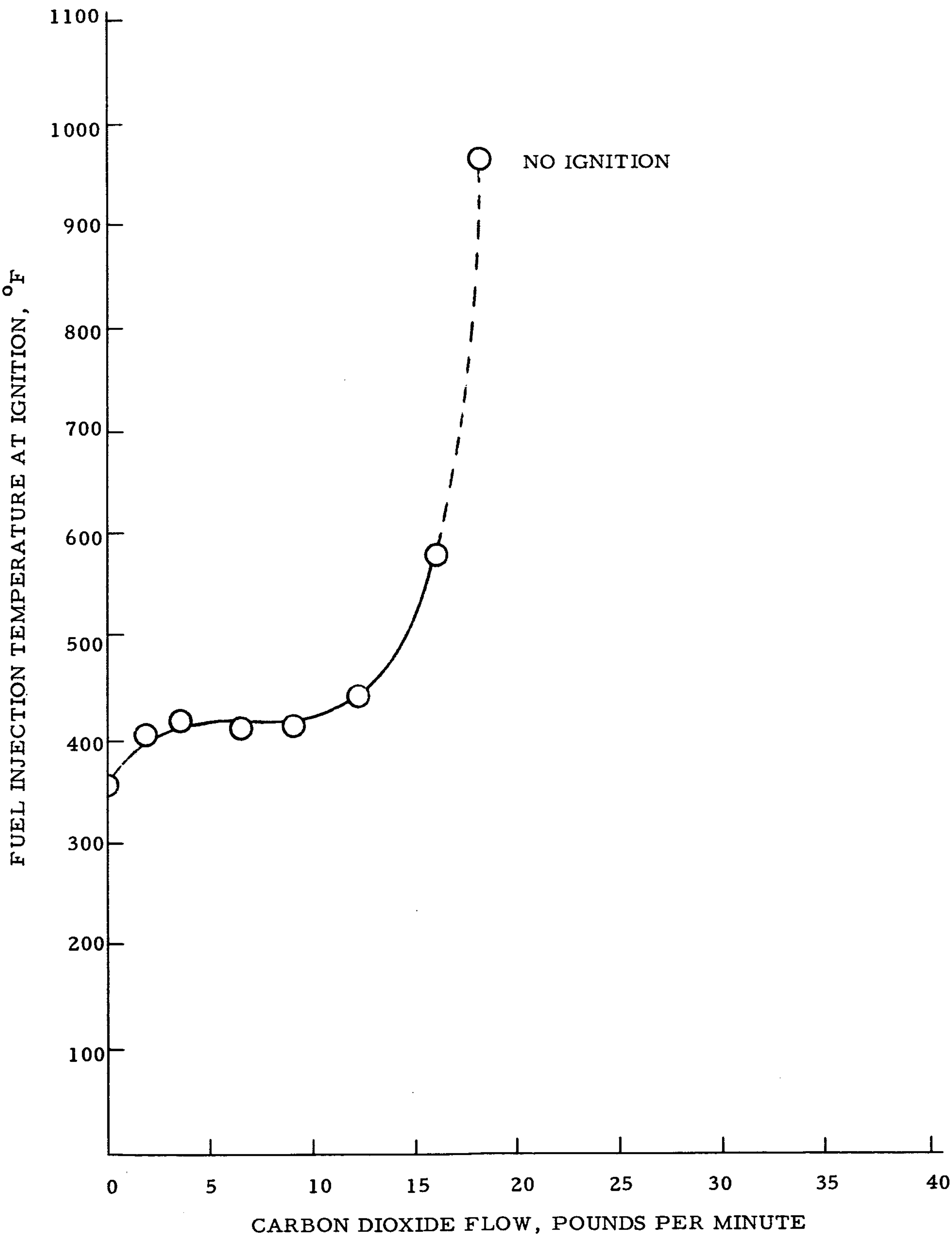

FIGURE 14. EFFECTS OF CARBON DIOXIDE ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 3/2 OXYGEN/RP-1 MIXTURES

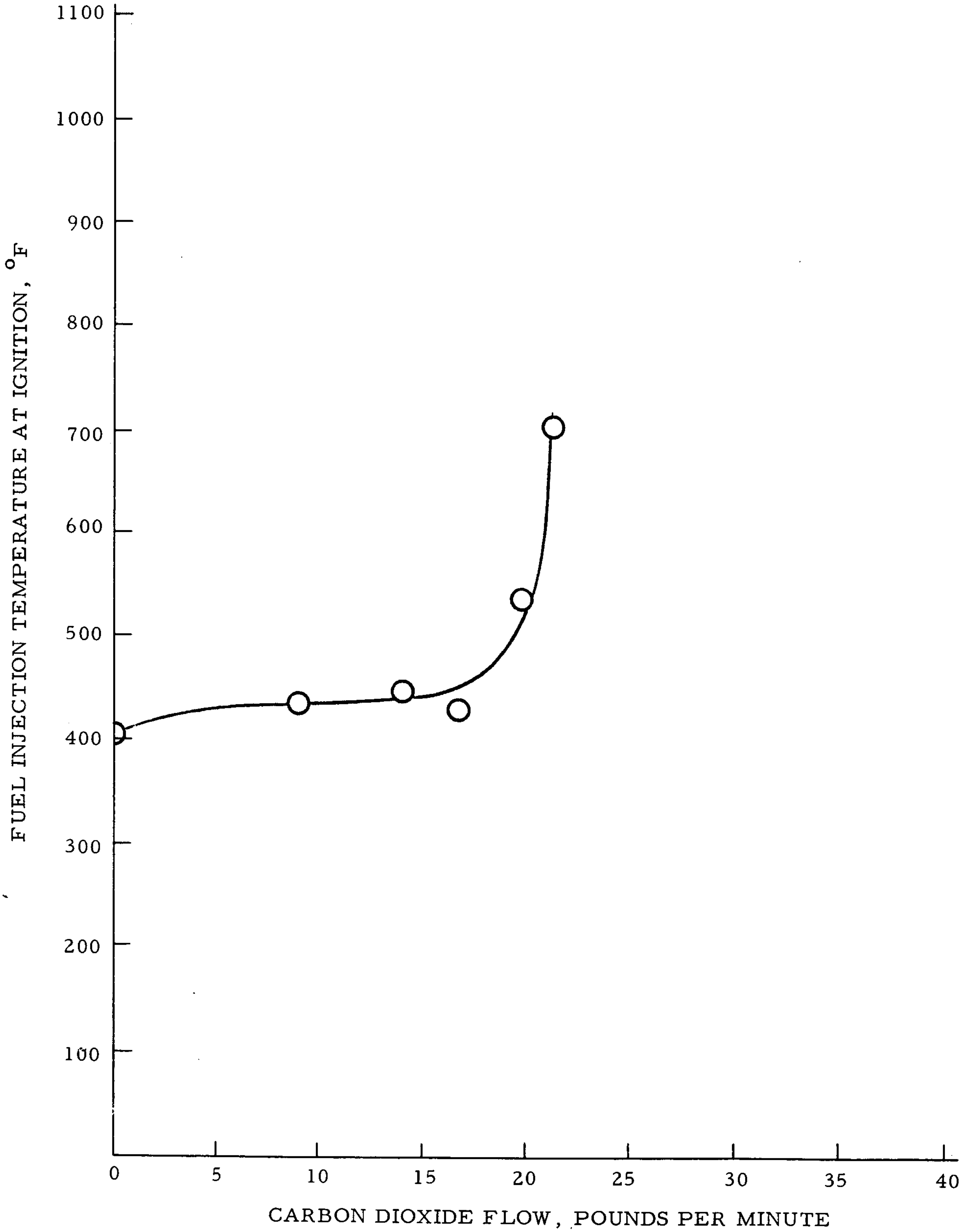

FIGURE 15. EFFECTS OF CARBON DIOXIDE ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 6/1 OXYGEN/RP-1 MIXTURES

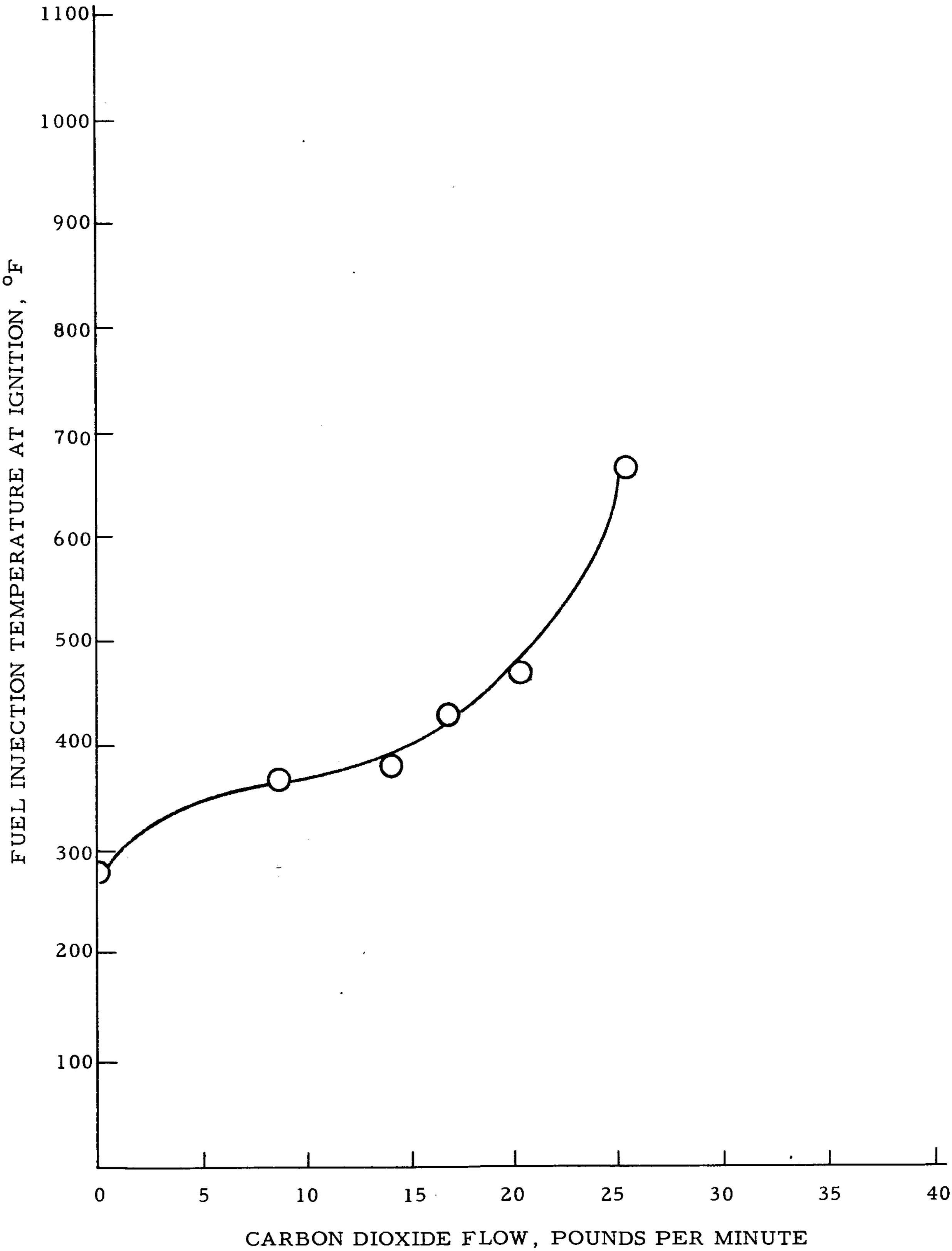

FIGURE 16. EFFECTS OF CARBON DIOXIDE ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 6/4 OXYGEN/RP-1 MIXTURES

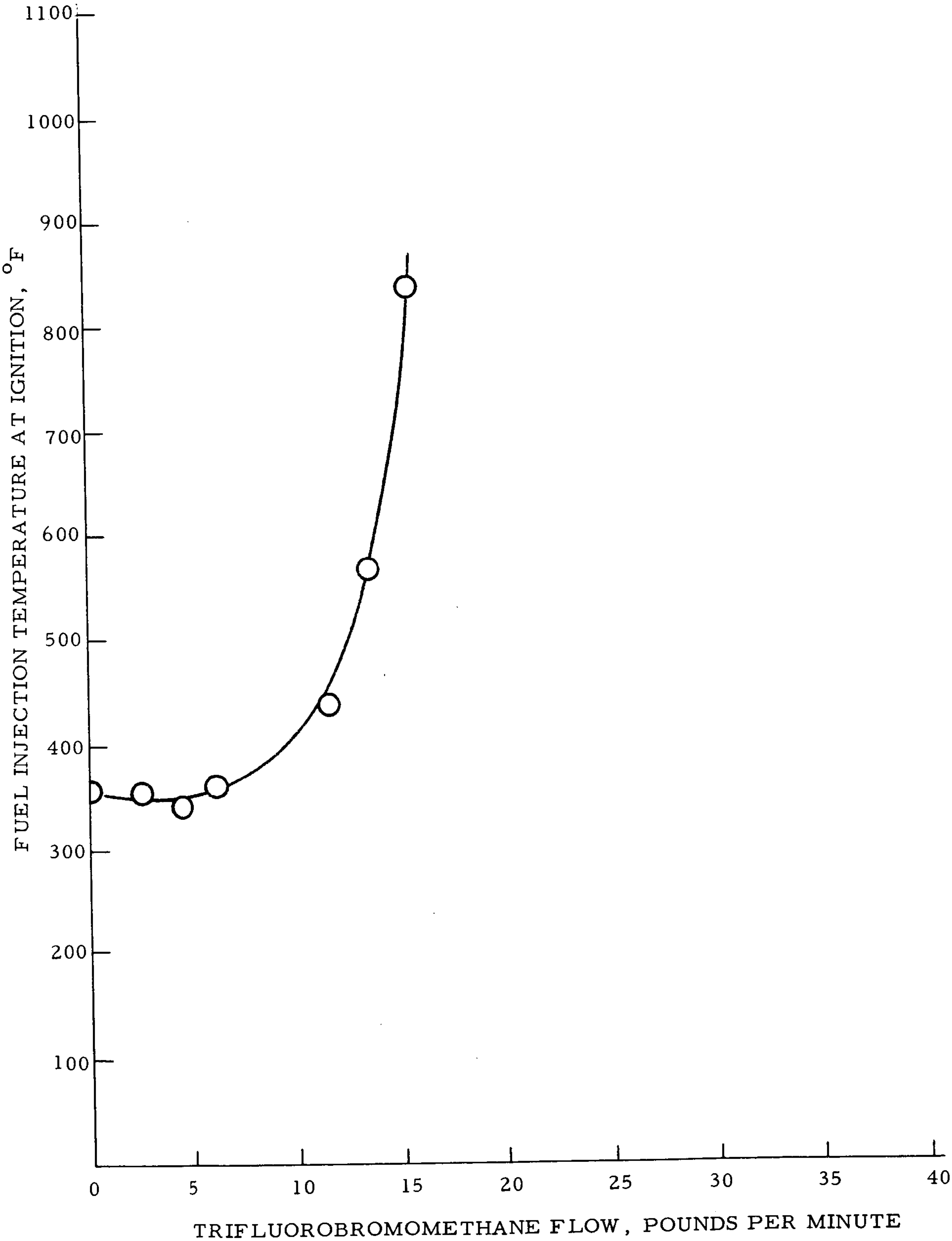

FIGURE 17. EFFECTS OF TRIFLUOROBROMOMETHANE ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 3/2 OXYGEN/RP-1 MIXTURES

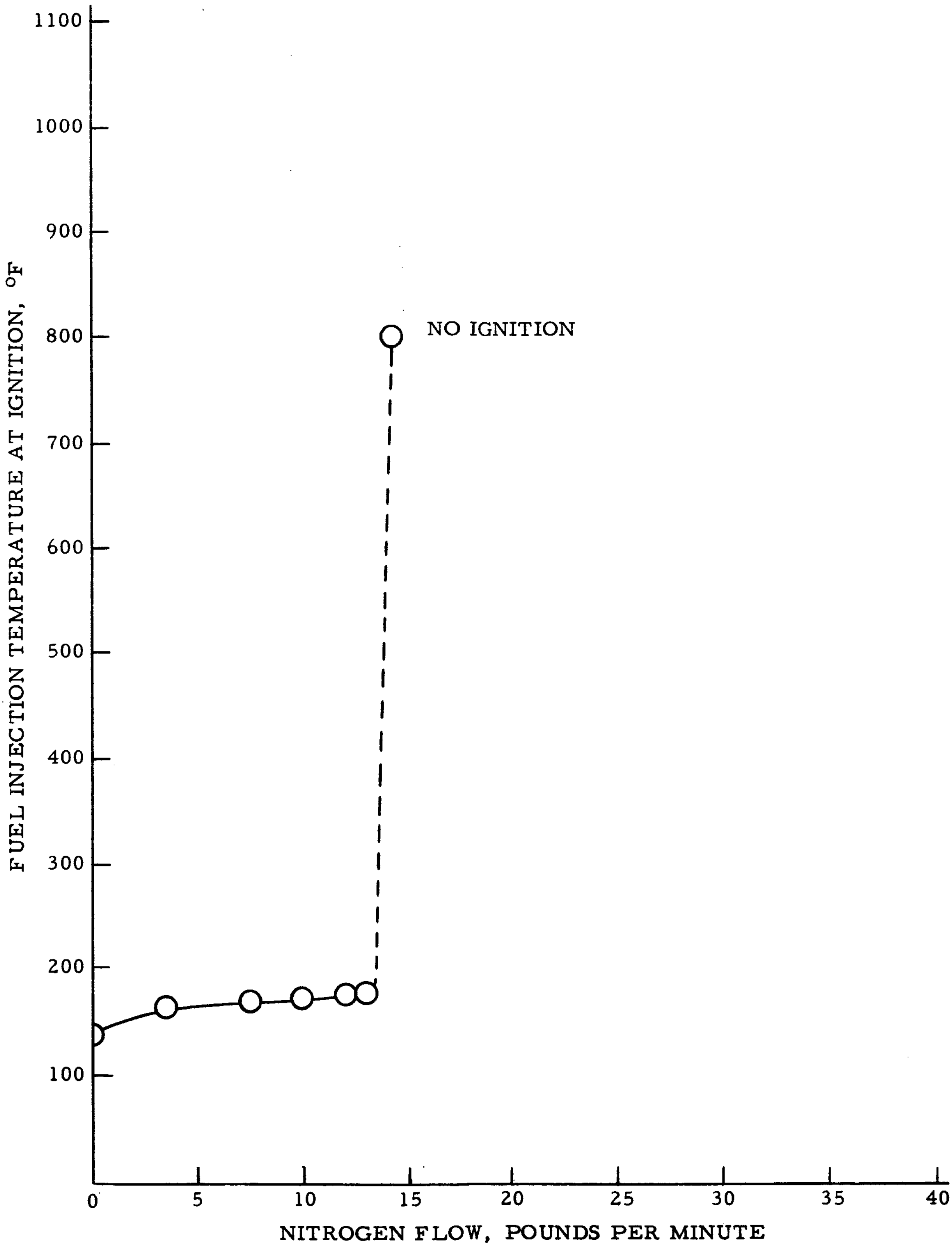

FIGURE 18. EFFECTS OF NITROGEN ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 3/1 OXYGEN/ETHYL ALCOHOL MIXTURES

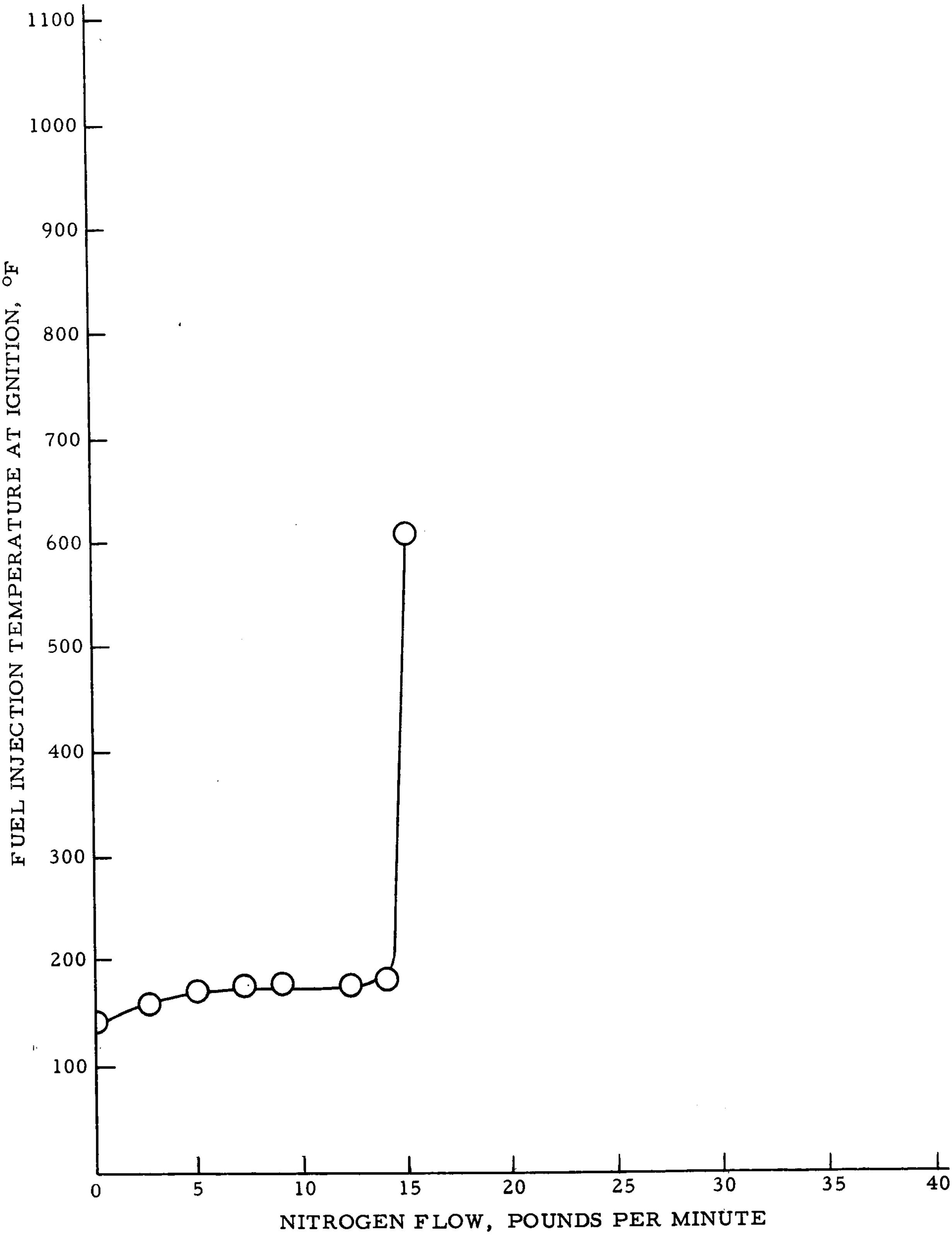

FIGURE 19. EFFECTS OF NITROGEN ON FUEL INJECTION TEMPERATURES REQUIRED FOR IGNITION OF 3/2 OXYGEN/ ETHYL ALCOHOL MIXTURES

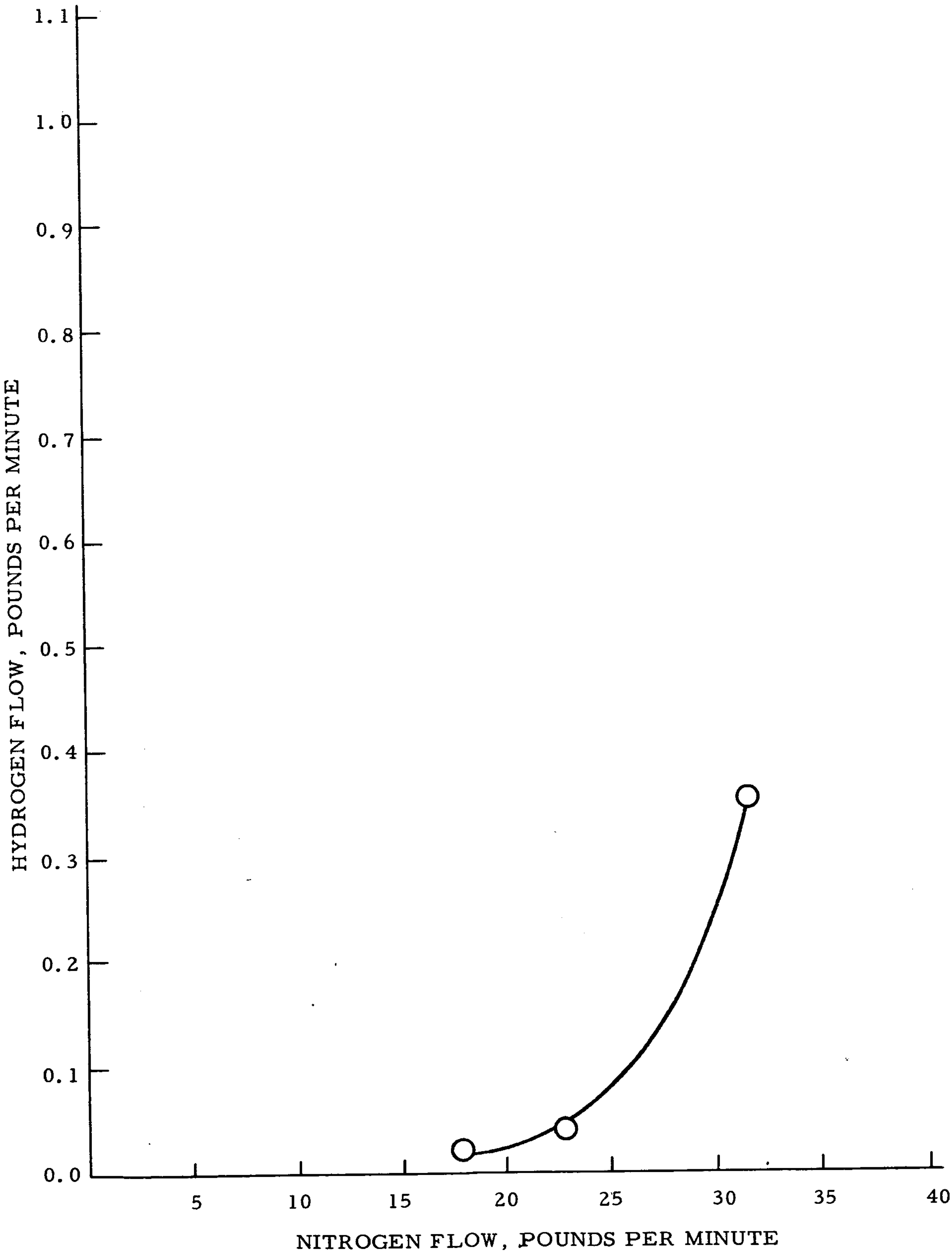

FIGURE 20. EFFECTS OF NITROGEN ON MINIMUM QUANTITIES OF HYDROGEN REQUIRED FOR IGNITION OF MIXTURES CONTAINING THREE POUNDS OF OXYGEN

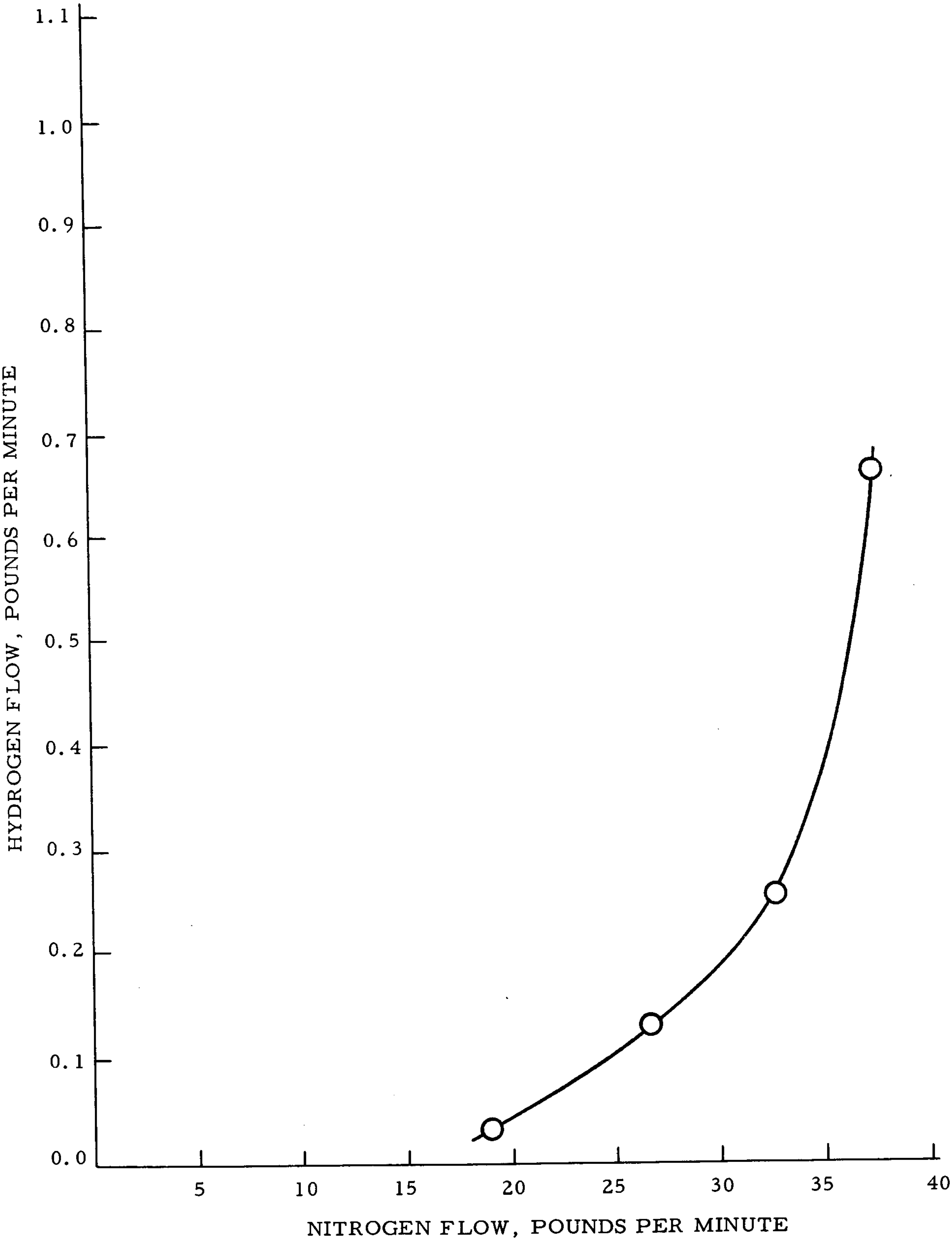

FIGURE 21. EFFECTS OF NITROGEN ON MINIMUM QUANTITIES OF HYDROGEN REQUIRED FOR IGNITION OF MIXTURES CONTAINING SIX POUNDS OF OXYGEN

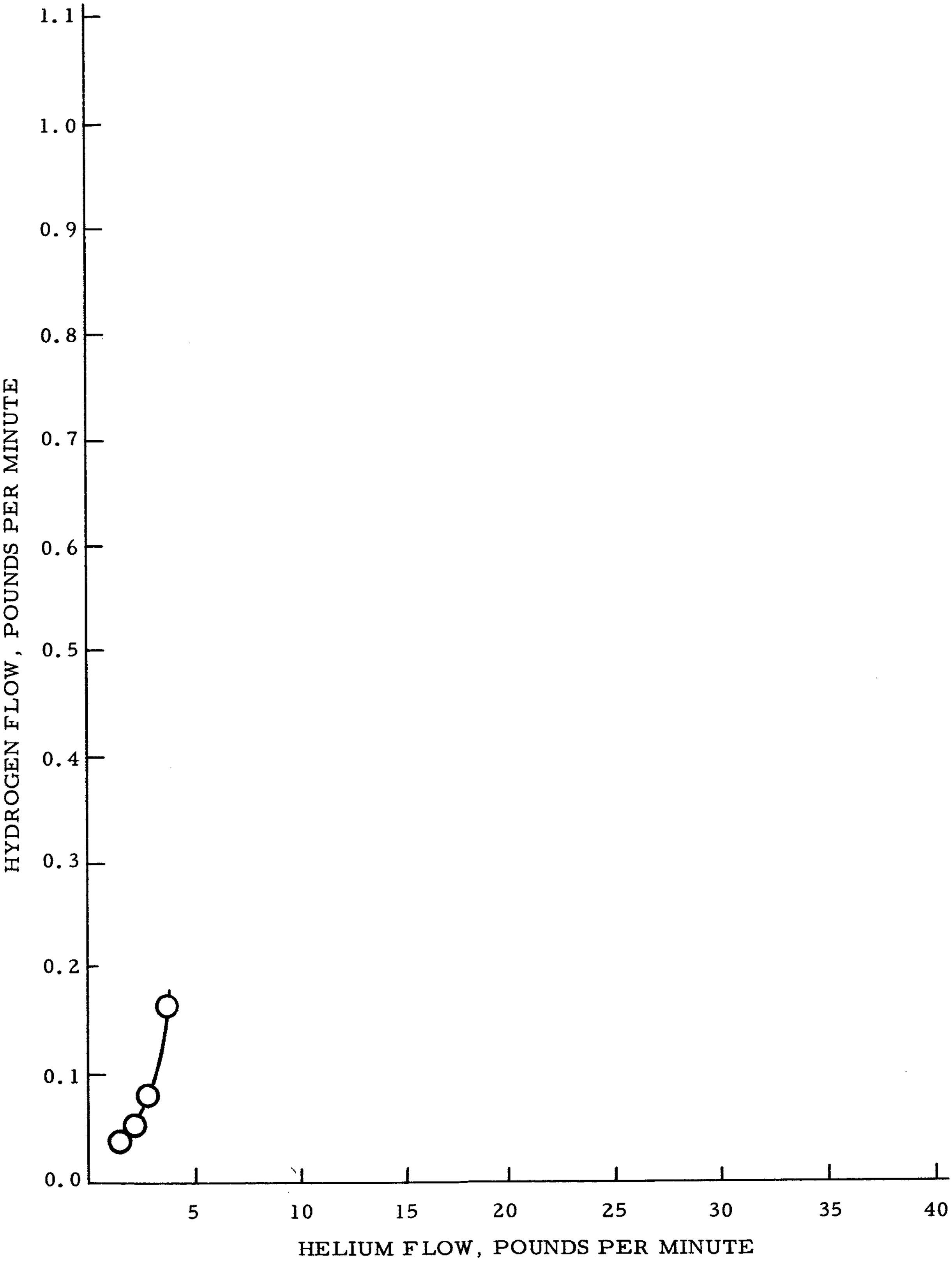

FIGURE 22. EFFECTS OF HELIUM ON MINIMUM QUANTITIES OF HYDROGEN REQUIRED FOR IGNITION OF MIXTURES CONTAINING THREE POUNDS OF OXYGEN

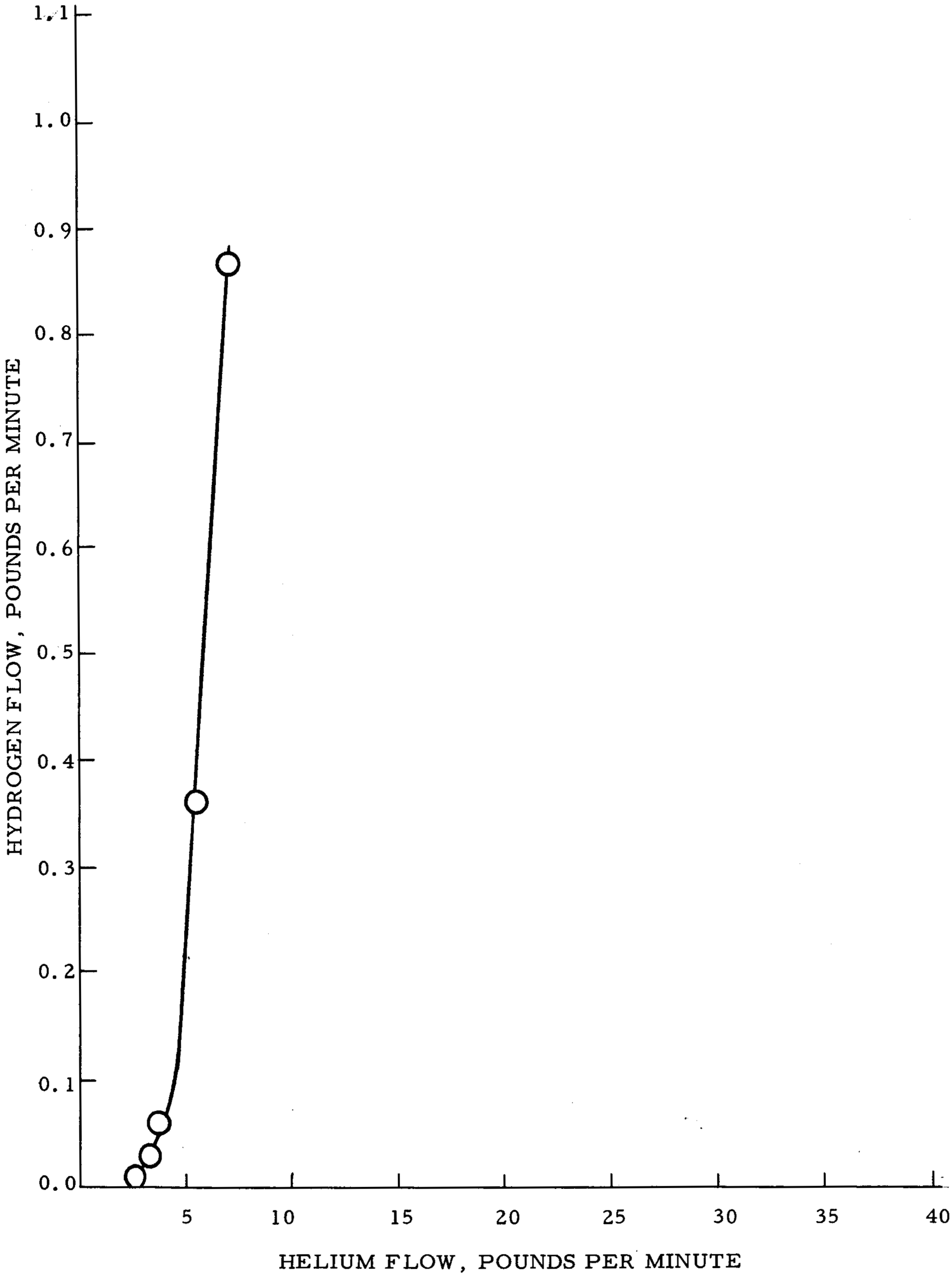

FIGURE 23. EFFECTS OF HELIUM ON MINIMUM QUANTITIES OF HYDROGEN REQUIRED FOR IGNITION OF MIXTURES CONTAINING SIX POUNDS OF OXYGEN

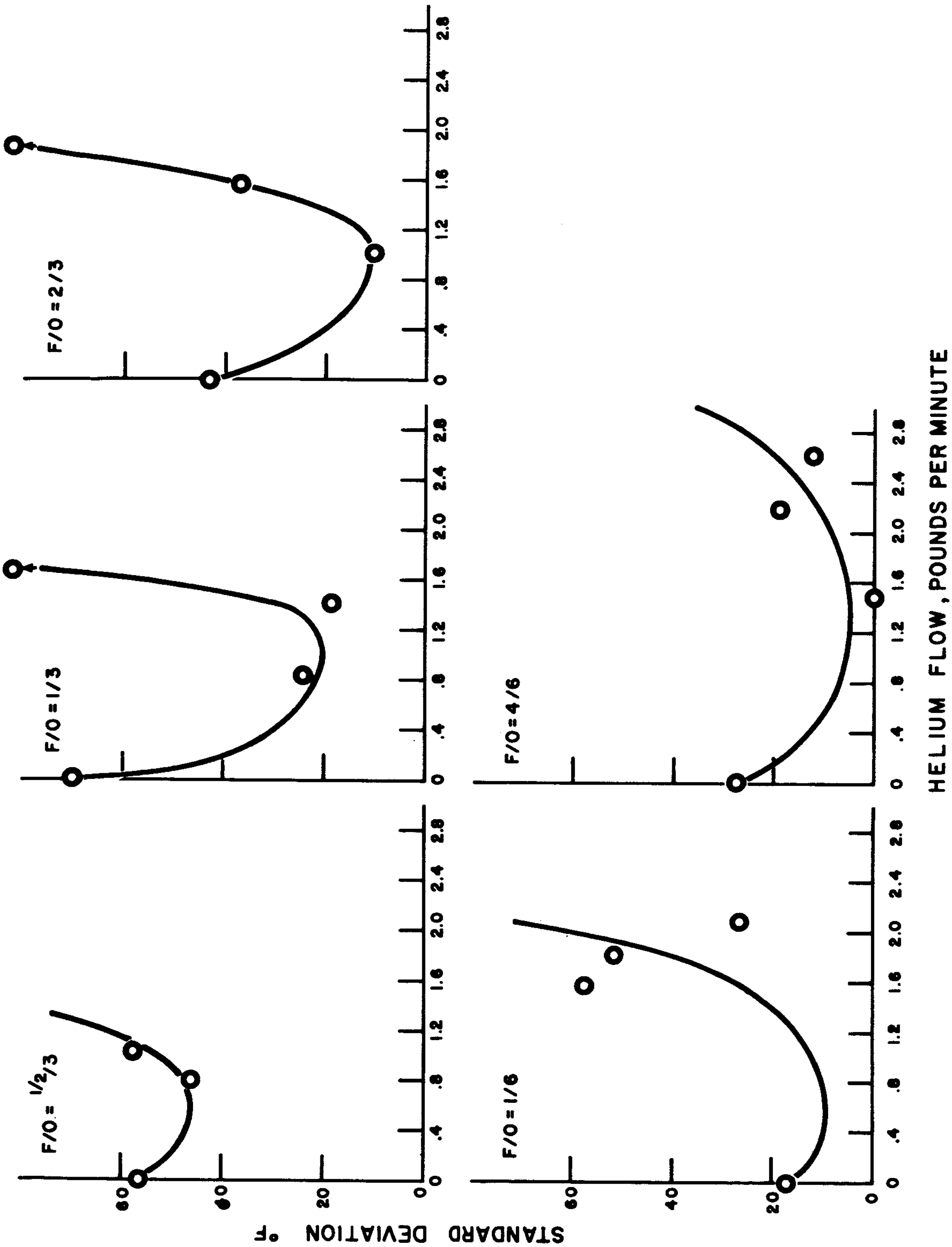

FIGURE 24. REPRODUCIBILITY OF FUEL INJECTION TEMPERATURES FOR THE SYSTEM, RP-1 + O_2 + He

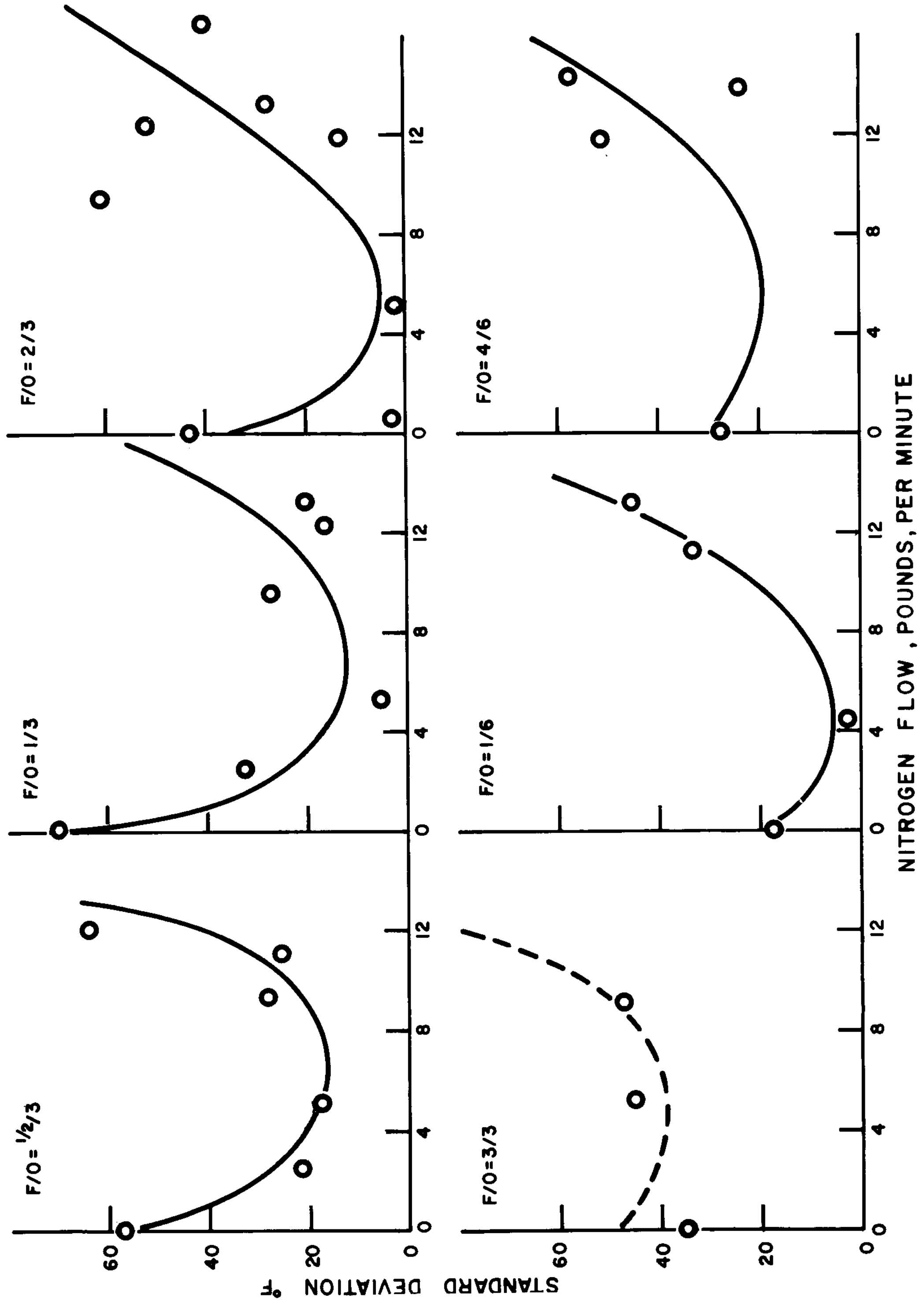

FIGURE 25. REPRODUCIBILITY OF FUEL INJECTION TEMPERATURE FOR THE SYSTEM, RP-1 + O_2 + N_2

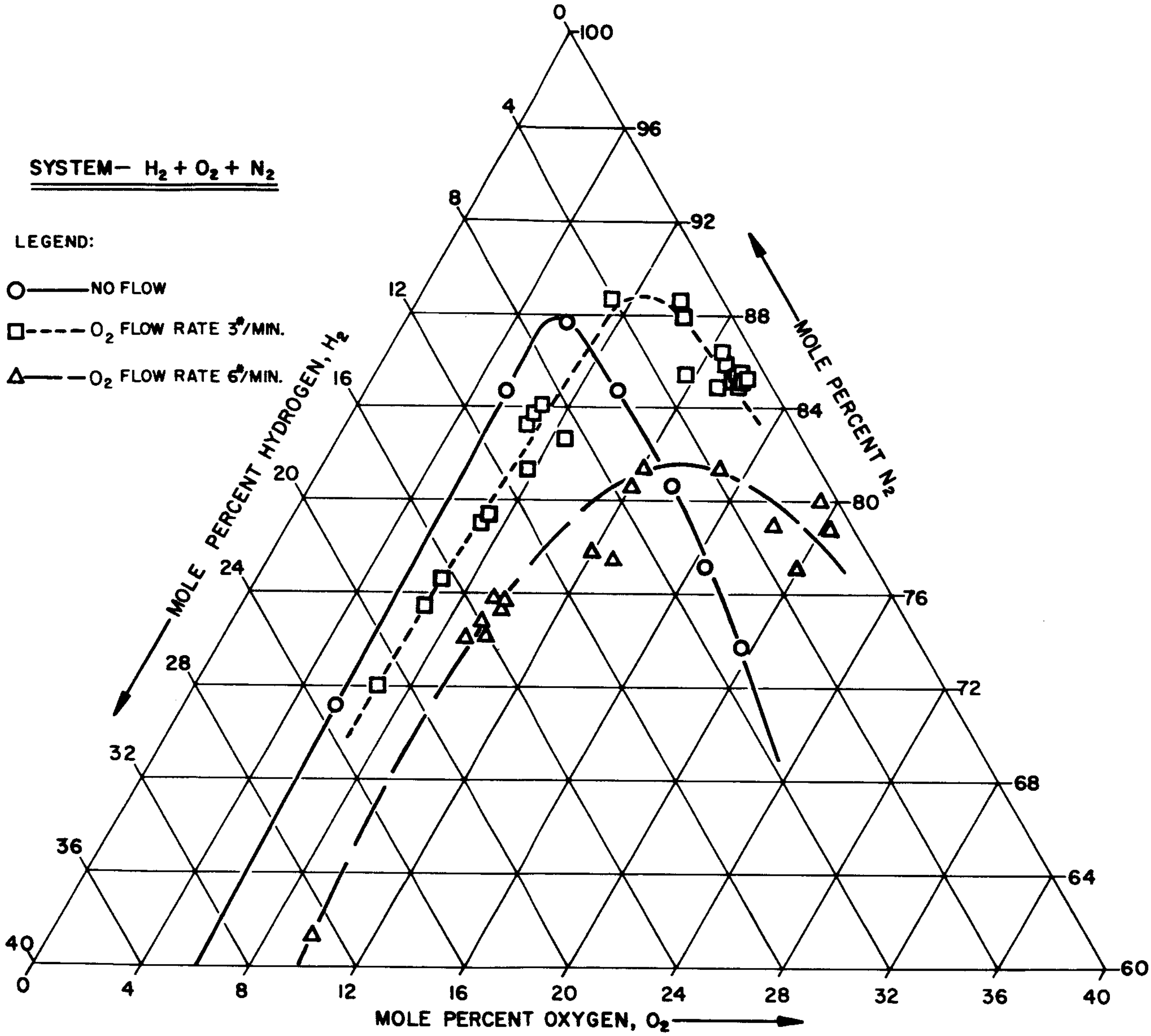

FIGURE 26. EFFECT OF FLOW RATES ON FLAMMABILITY DATA FOR THE SYSTEM $H_2 + O_2 + N_2$

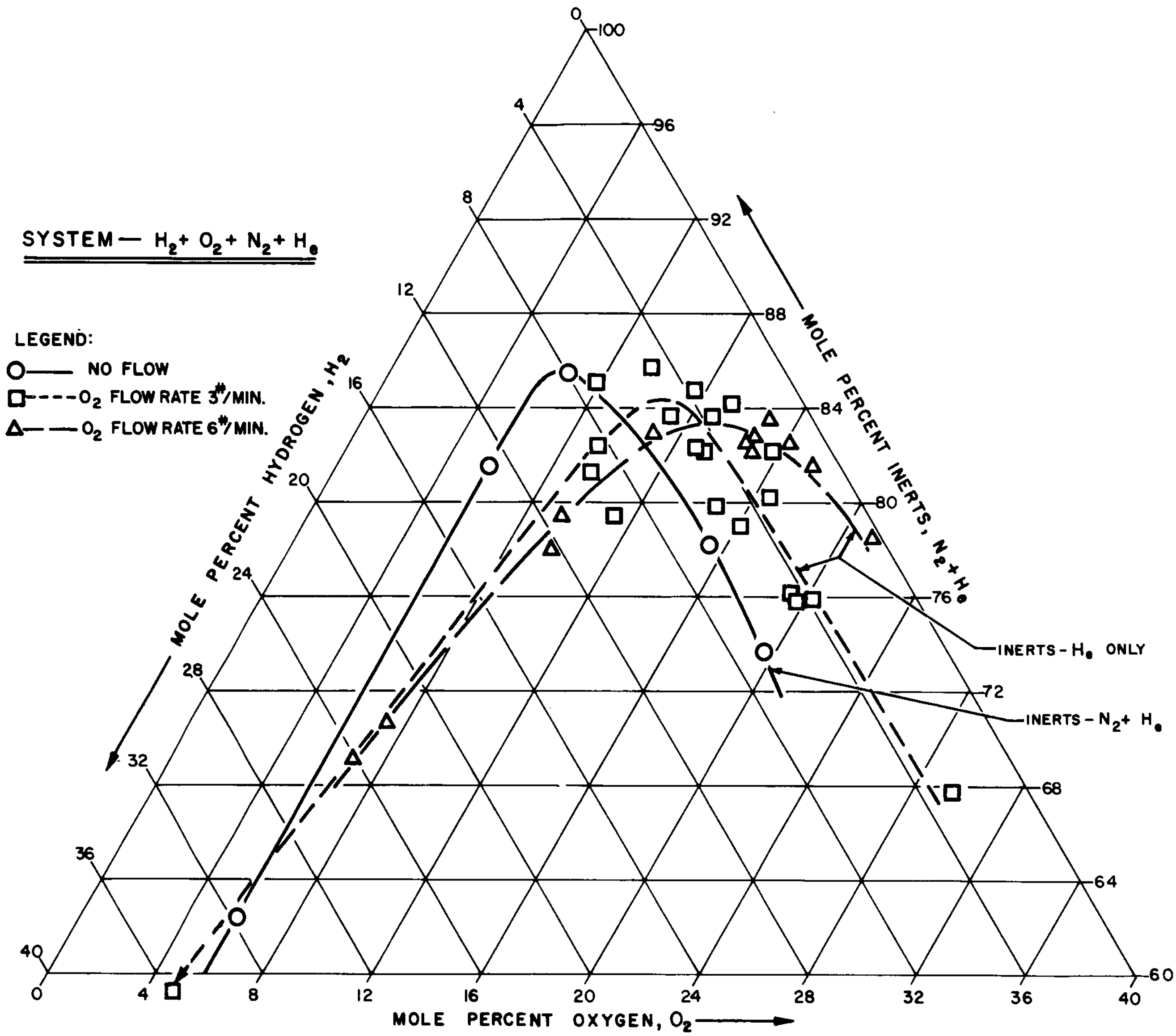

FIGURE 27. EFFECT OF FLOW RATES ON FLAMMABILITY DATA FOR THE SYSTEM H_2 + O_2 + N_2 + He

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